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Measuring Moisture in Living Foliage Using a Radio Frequency Open Wire Transmission Line

Final Report

Contract #12-11-204-12

MONTANA STATE UNIVERSITY
Electronics Research Laboratory
BOZEMAN, MONTANA

ERL

Measuring Moisture in Living Foliage
Using a Radio Frequency
Open Wire Transmission Line

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Submitted to
U. S. Forest Service

by

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ABSTRACT

This report covers work done in the past few months at the Electronics Research Laboratory of Montana State University on the measurement of moisture in foliage by using RF energy and techniques. The foliage tested in the study included both cut samples of various foliages and a living stand of oats, wheat, and barley. The test circuits employed were open wire transmission lines both balanced and unbalanced, a resonant coaxial cavity, and a 10 GHz (10,000 MHz) attenuation circuit. The major conclusion of the report is that RF moisture sensing is feasible in living foliage and that remote moisture monitoring can be done without the use of an operator.

Measuring Moisture in Living Foliage
Using a Radio Frequency Open Wire Transmission Line

I. Introduction

The purpose of the work reported on herein was to study the feasibility of measuring living foliage moisture content using a Radio Frequency (RF) open wire transmission line. Previous work by Parker et al[1, 2] had indicated the possibility of sensing moisture in living foliage with an Open Wire Line (OWL). Parker and his co-workers were interested primarily in cataloging the dielectric properties of living foliage over a wide frequency range. Their results reflected a pronounced dependence on the moisture content of the foliage. For example the attenuation constant (α) showed an order of magnitude change for spruce trees in the Hoh rain forest as the spruce changed from wet to dry[1]. Other measured parameters such as dielectric constant, loss tangent, and phase constants also showed variation with moisture but not to as great an extent as the attenuation constant.

The general measurement procedure followed in reference one and two was to insert a balanced open wire transmission line into a foliage sample and to take short circuit and open circuit impedance readings on the line. Several alternatives are available in obtaining the impedance data, however. Resonant unbalanced lines (the line length is an integral multiple of quarter wavelengths at the measurement frequency) or non-resonant unbalanced lines may be used instead of the balanced OWL used in references one and two. The length, spacing and diameter of the transmission lines are functions of the frequency chosen for the measurements. Consideration must

be given these and several other alternatives because the RF moisture measuring system accuracy, sensitivity and ease of use will vary as various alternatives are chosen. Thus even though a general procedure had been established[1, 2] to measure foliage dielectric properties the specific measurement of moisture in foliage using RF techniques had not been extensively examined.

One of the major benefits from a successful development of an RF foliage moisture measuring device would be the obtaining of rapid foliage moisture data for use with the fire danger rating system. Such a device would allow on-the-spot field measurements and could, perhaps, be adapted for use at remote sampling sites. If remote operation were to prove feasible, a sampling network could be established with the data transmitted by telemetry to a central point for processing. Most of the RF moisture measurement systems investigated and discussed in this report were weighed and judged with respect to application to the fire danger rating system. This helped keep the research pertinant to the existing problem and also served to define the area of study.

II. Outline of the Study

Since the work undertaken on this contract was to study the feasibility of measuring moisture in foliage with RF techniques, a number of possible techniques were considered. Eventually several of the techniques that appeared to offer the most promise were constructed and tests were performed in the laboratory to establish the capabilities and limitations of each technique. The area of study was brought into focus through the considerations discussed in the next paragraph.

Frequency Range

The frequency at which the moisture sensing RF systems were built was bounded by two major considerations. First the frequency had to be high enough that the physical dimensions of the sensing circuit were reasonable. Thus a lower frequency limit of about 10×10^6 cps (10 MHz) was expected since the wavelength at this frequency is 30 meters. A quarter wavelength line would then be about twenty-five feet long. Lines much longer than this would be too cumbersome to use except, perhaps, in a permanent field site. The upper frequency limit is set by the cost and availability of equipment and the amount that moisture in the foliage affects the RF signal. Thus it is known (see p. 749, ref. 3) that RF absorption in the atmosphere caused by water vapor peaks at about 21×10^9 cps (21 GHz). Since test equipment is not readily available at this frequency, the upper frequency limit was set as 10 GHz where test equipment is readily available and is relatively inexpensive. Even at 10 GHz it was expected that moisture content in foliage could be measured

by measuring α, the attenuation constant. The frequency range of interest for this study was then defined as being between 10 MHz and 10 GHz.

Type of Sensing Circuits

The type of sensing circuit used to measure the moisture was defined to a large extent by what RF parameter of the foliage was to be measured. Thus if so called "secondary parameters" such as relative dielectric constant (ε_r), loss tangent (δ), or conductivity (σ) were to be measured there were two practical approaches. The OWL could be used by taking open and short circuit impedance data and from this data calculating the secondary parameters. A second method of measuring the secondary parameters would employ a resonant structure such as a shorted quarter wave long OWL or a half wave long metal box at higher frequencies. By measuring the resonance curve of the structure in air and then in (or filled with) the foliage the secondary parameters could be calculated. It was also expected that one or more of the primary parameters such as the short and open circuit impedances, the resonance response, or the shift in frequency of the resonance might prove sufficient to sense the foliage moisture.

By going to the 10 GHz frequency another sensing circuit became possible. At this frequency the free space wavelength is very small (3 cm or slightly more than one inch). Thus a sample of foliage could be placed in a test box whose dimensions were on the order of a few inches and the box placed in the RF circuit. The change in energy transmitted through the box when it was empty and when it was filled with the sample

gave a direct measure of the attenuation constant (relative to the atmosphere surrounding the test circuit).

Three major types of sensing circuits were studied. They were the Open Wire Line (OWL), a resonant cavity, and a 10 GHz attenuation test circuit. Several variations of the OWL were studied including balanced two wire lines open and short circuited, terminated two wire lines, and an unbalanced OWL over a ground plane with open and short circuit terminations.

Types of Foliage Used for the Project

The foliage used for the study included whole sagebrush plants (uprooted), cut alfalfa hay, growing wheat, oats, and barley, and cut lawn grass. The reasons for the use of each type of foliage will be more fully explained in Section IV. Primarily they were chosen as representative of the type of foliage likely to be encountered in field use of the moisture meter or for availibility and range of expected moisture content. For instance, the cut lawn grass was readily available in the large quantities needed and had a moisture range of about 400% down to 5-6% (% moisture = weight of water in the sample divided by the sample dry weight). Thus it was extensively used in calibration tests and bulk density tests.

Major Results

In general, the results of the study are that the presence of moisture in foliage both living and non-living is detectable with various RF test circuits. As the water content varies certain quantities

describing propagation in the test circuit also vary in a repeatable manner. With most of the test circuits the variation was not linear and tended toward saturation at moisture contents above 100%. The 10 GHz system was an exception to this with a nearly linear change in attenuation with moisture content and little tendency toward saturation. The major problem encountered with any test structure involving cut foliage was with the bulk density of samples whose moisture content exceeded 100%. The results from each type of test circuit are briefly presented below. More detailed results are given in Section V.

Unbalanced OWL with a Ground Plane

This test circuit was operated from 15 MHz to 90 MHz in discreet steps. The optimum frequency appeared to be 50 MHz for a non-resonant line terminated in an open circuit. The most promising circuit, however, was the unbalanced OWL operated as a resonant shorted line at 1/4 or 3/4 wavelength. This test setup does not have the bulk density problem since a fixed set of grass is monitored for the whole growing season. The data shows saturation at about 50% moisture content but the curve can be read out to at least 175%. The region of highest probable accuracy with this system would be for moistures between about 10% to 70%.

OWL Box Structures

Several variations of open wire lines surrounded by a test box were investigated. The size and type of box were varied as were the length of line and type of termination. The tests showed in general a

nearly linear change of input impedance with moisture content of the lawn grass used in most of the tests until the moisture reached 100%. Saturation then occurs and the bulk density problem becomes severe. The tests with grasses running from 100% to 400% yielded a rather scattered set of impedance points. These test structures show a good sensitivity from 0 to 100% moisture content.

200 MHz Cavity

A coaxial cavity was constructed to measure the secondary parameters as previously discussed. Tests demonstrated that when the cavity was filled with grass with moisture content in excess of about 30% the loss in the cavity was so high that no signal was available for measurement. In part this problem could be overcome using a source with higher power. The 200 MHz source available for the test generated one milliwatt of 200 MHz power. A 100 milliwatt source would give two orders of magnitude more detection sensitivity and possibly extend the useful range of the cavity. A second set of tests were run filling only a small volume at one end of the cavity with grass. The cavity quality factor* was measured as a function of moisture content of the grass for moistures between 0 and 150%. The curve showed highest sensitivity between 0 and 100% and rapid saturation above 100%. Bulk density variation was again a problem above 100% moisture although the sensitivity offered by this test circuit was quite high until saturation.

* The cavity Q or quality factor is defined as the energy stored in the cavity per cycle divided by the average energy lost per cycle. To a good approximation it is given by the resonant frequency divided by the difference in frequencies at the half power points of the cavity response curve.

10 GHz Test Circuit

This test circuit used the smallest amount of foliage (20-30 grams) because of the short wavelength. The results obtained with this circuit indicated a linear change in attenuation (proportional to α) with moisture in the foliage even for very wet samples. Small grains such as wheat, barley, oats, and corn have also been measured for moisture content in this circuit with similar linear variation of attenuation with moisture content. Bulk density is a problem in measuring foliage with this circuit and the small test volume could be a problem. Foliage samples may have to be chopped or ground to fit in the test box for some types of foliage. On the other hand it is very easy to obtain enough sample to fill the test box and run a moisture test with this circuit.

III. Analysis

In this section, the equations needed for the study are developed and discussed. The section was kept as brief as possible since all the analytic work is "standard" and appears in other papers[1, 2] and in textbooks (see referances 4 and 5, for instance). The report would be incomplete without some consideration of the pertinent equations, however.

The Open Wire Line (OWL) Equations

The description of propagation of waves along a transmission line is given by the well-known telegraph equations[5].

$$\frac{\partial I}{\partial x} = gV + C\frac{\partial V}{\partial t} \tag{1}$$

$$\frac{\partial V}{\partial x} = rI + L\frac{\partial I}{\partial t} \tag{2}$$

where I = current

V = voltage

g = susceptance per unit length

C = capacitance per unit length

L = inductance per unit length

r = resistance per unit length

x = distance down the line

If one assumes sinusoidal excitation on the line (all experiments covered in this report were for sinusoidal excitation) one can replace the time partial deriviatives in (1) and (2) with $j\omega$, where $j = \sqrt{-1}$, $\omega = 2\pi f$, f = excitation frequency.

then

$$\frac{\partial I}{\partial x} = (g + j\omega C)V = yV \qquad (3)$$

and

$$\frac{\partial V}{\partial x} = (r + j\omega L)I = zI \qquad (4)$$

Equations (3) and (4) can be combined to give the wave equation

$$\frac{\partial^2 V}{\partial x} - zyV = 0 \qquad (5)$$

or

$$\frac{\partial^2 I}{\partial x} - zyI = 0.$$

The solution to (5) may be written as

$$V = V_1 e^{-\sqrt{zy}x} + V_2 e^{\sqrt{zy}x} \qquad (6)$$

or

$$I = I_1 e^{-\sqrt{zy}x} + I_2 e^{\sqrt{zy}x} \qquad (6a)$$

The propagation constant is designated by

$$\Gamma = \sqrt{zy} = \alpha + j\beta \qquad (7)$$

where α = attenuation coefficient

β = phase change coefficient

The subscripts on I_1, V_1, I_2, and V_2 refer to a forward wave on the line (1 subscript) or a reflected wave (2 subscript). Note that by using (7) or (8) in (3) or (4) that the forward voltage and current waves are related by

$$V_1 = -\sqrt{z/y}\, I_1 = -Z_0 I_1 \qquad (8)$$

$$V_2 = \sqrt{z/y}\, I_2 = Z_0 I_2 \qquad (9)$$

where Z_o = characteristic line impedance. Now one can write the line input impedance as

$$Z = \frac{V}{I} = Z_0 \frac{\left[-I_1 e^{-\Gamma x} + I_2 e^{\Gamma x}\right]}{\left[I_1 e^{-\Gamma x} + I_2 e^{\Gamma x}\right]} \tag{10}$$

For a short-circuited line $I_1 = I_2$ and

$$Z_{sh} = Z_0 \tanh \Gamma x \tag{11}$$

For an open-circuited line $V_1 = V_2$ and by using 9 and 10 in 11 it is easy to show

$$Z_{op} = Z_o \coth \Gamma x. \tag{12}$$

Hence

$$Z_0 = \sqrt{Z_{op} Z_{sh}} \tag{13}$$

The last expression is the key to the measurements made on the OWL. By measuring the open and short-circuit impedances one obtains Z_o which is related to the propagation constant through (11) and (12). The value of Γ gives α and β which in turn give the physical characteristics of the media. It can be shown that (ref. 1 and Appendix A)

$$\alpha^2 = \frac{1}{2} \left(\frac{\omega}{c}\right)^2 \{[\varepsilon_r{}^2 + \delta\varepsilon_r]^{\frac{1}{2}} - \varepsilon_r\} \tag{14}$$

$$\beta^2 = \frac{1}{2} \left(\frac{\omega}{c}\right)^2 \{[\varepsilon_r{}^2 + \delta\varepsilon_r]^{\frac{1}{2}} + \varepsilon_r\} \tag{15}$$

where $c = 3 \times 10^8$ meters/sec.

ε_r = relative dielectric constant of the medium surrounding the line

$\delta = \frac{\sigma}{w\varepsilon_o}$ = loss tangent of the medium

σ = conductivity of the medium

A digital computer was used to reduce the data taken on the OWL since it is obviously a tedious task to do all the calculations by hand. The use of these equations is discussed further in section IV and V.

The Resonant Cavity Equations

The resonant cavity was investigated since it offered a direct and fairly rapid means of measuring relative dielectric constant (ε_r) and loss tangent (δ). For a metal box to resonate it is necessary that the length of the box be some integral multiple of a half wavelength. That is

$$L = n\lambda/2; \qquad n = 1, 2, 3, \ldots \tag{16}$$

A coaxial cavity was picked for this study since it could be designed to have reasonable physical dimensions in the frequency range of the available signal generator. For such a cavity it can be shown that [4]

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}}$$

where

$c = 3 \times 10^8$ meters/sec.

f = the operating frequency

ε_r = relative dielectric constant of the material in the cavity

For resonance then

$$L = \frac{n\lambda}{2} = \frac{nc}{2f_r\sqrt{\varepsilon_r}} \tag{17}$$

and for resonance in air

$$L = \frac{n}{2} = \frac{nc}{2f_o} \tag{18}$$

Hence

$$\varepsilon_r = \left(\frac{f_o}{f_r}\right)^2 \qquad (19)$$

where

f_o = resonant frequency with air in the cavity

f_r = resonant frequency with material in the cavity

The Q or quality factor of the cavity is closely approximated by

$$\frac{1}{Q} \simeq \frac{\Delta f}{f_r} \qquad (20)$$

where

Δf = 3 db bandwidth of the cavity

$= (f_{+3} - f_{-3})$

For an imperfect dielectric filling the cavity one can write(4)

$$\frac{1}{Q} = \frac{\sigma}{\omega \varepsilon r \ \varepsilon_o} = \delta \simeq \frac{\Delta f}{f_r} \qquad (21)$$

Equation (21) can also be solved for the conductivity σ to yield

$$\sigma = 2\Pi \varepsilon_o \Delta f \left(\frac{f_o}{f_r}\right)^2 \qquad (22)$$

where $\varepsilon_o = 8.854 \times 10^{-12}$ farad/meter.

Equations (19), (21), and (22) were to be used to evaluate the foliage in the resonator.

Microwave Moisture Measurement

The foliage measured with the microwave (10 GHz) test setup was all cut samples. The foliage was viewed as being a non-ideal dielectric material with a loss tangent that varied with water content. Following this line of reasoning allows an analytical model to be devised. Writing one of the basic electromagnetic field equations in terms of a material with a

non-ideal dielectric allows a complex relative dielectric constant to be defined as

$$\varepsilon = \left[\varepsilon_r - j \frac{\sigma}{w e_o}\right] \tag{23}$$

Now for free space propagation the propagation constant can be written as

$$\Gamma = \alpha + j\beta \doteq - \frac{j\omega}{c}\sqrt{\varepsilon} \tag{24}$$

or

$$\Gamma = - \frac{j\omega}{c} \left[\varepsilon_r - j \frac{\sigma}{w e_o}\right]^{\frac{1}{2}} \tag{25}$$

This expression may be closely approximated by

$$\Gamma \simeq \frac{-j\omega}{c} \sqrt{\varepsilon_r} \left[1 - \frac{j\sigma}{\varepsilon_r 2 w e_o}\right] \tag{26}$$

as long as $\sigma/2\varepsilon_o\varepsilon_r\omega$ is small compared to one. Then α the attenuation coefficient is given by

$$\alpha \approxeq \frac{\sigma}{2c\sqrt{\varepsilon_r \varepsilon_o}} \tag{27}$$

It was expected that σ, the conductivity of the foliage to be measured, would be highly dependent on if not proportional to the amount of water contained in the foliage. Hence by using or approximating free space propagation conditions and measuring the attenuation through a sample of foliage, a measure of the amount of water present would be obtained. It is not necessary in practice to approximate free space propagation. A similar development could be done for propagation through the foliage contained in a waveguide with a similar result. Equation (27) demonstrates the theory that led to the 10 GHz test setup, however.

Bulk Density Effects

Bulk density effects have been mentioned several times in the first part of this report. It is appropriate in this section to analyze why it plays such an important role in the measurement of moisture in foliage when using RF techniques.

All of the measurement techniques discussed in this report share one characteristic. Each system has a specific volume of space throughout which electric and magnetic fields exist. In the case of the open wire lines this volume excludes the actual lines, but includes the space between them and a sensing volume outside the lines. For the 200 MHz cavity the volume was the end of the cavity forming the test cell while for the 10 GHz system the volume was the test cell inserted in the transmission system. Each of the RF systems is sensitive to changes in the dielectric within this test volume; indeed this is the reason that moisture and moisture changes can be detected. It is obvious, however, that not only will the RF system respond to changes in the amount of moisture within the material but also to the amount of material and the way the material occupies the test volume. At first glance this would not appear to a problem since the simple expedient of weighing each sample to be placed in the volume and tested is a means of controlling the amount of material in the test volume. Consider the following, however. Suppose the foliage to be tested for moisture has an oven dry density of about 0.5 g/cc. For a 1000 g weight of this material (assuming no air space in the volume) the volume occupied by the sample would simply be 2000cc. Now suppose one has the same foliage at 300% moisture content. The total sample weight of 1000 grams would then be made up of 750 g water and 250 g dry material. The volume occupied by the 300% moisture sample

would be

$$\text{Volume} = \frac{250}{.5} + \frac{750}{1} = 1250 \text{ cc.} \qquad (28)$$

Hence even though the sample weights considered were identical, the volume occupied by the wet sample was only 62.5% that of the dry sample. It is also seen that as the difference in density between water and the dry weight density of the foliage to be measured increases the difference in equal weight volumes of wet and dry samples will increase. The error caused by this volume difference for equal weight samples is that each sample does not occupy the RF test volume in the same way. Hence the RF fields within the volume are changed by not only the moisture difference between the samples but also by the volume difference.

It is also impractical to consider equal volume samples simply because of difficulty in defining the equal volume. Dry foliage tends to "fluff up" and be relatively hard to pack. Hence air pockets or spaces exist in a sample box filled with the dry material. Wet foliage, on the other hand, usually will pack and compress leaving smaller air spaces in the filled sample box. It is difficult to define the amount of packing needed to obtain a constant density volume of foliage over a wide moisture range. Laboratory experiments conducted during this study demonstrated this difficulty and it was shown that most of the variations of test data from samples in test boxes was due to these packing or volume problems.

One further point should be discussed in connection with the bulk density question. This is the homogenuity of the sample under test. The RF test circuits should operate in an optimum fashion if a homogeneous sample of the dielectric to be measured were placed in the test volume.

Actually this never happens since air space, leaves, stems, etc. all combine to make up a given foliage sample. The RF circuits will all perform well even on non-homogenous samples as long as the lack of homogeneity can be maintained constant throughout the samples. Errors in the moisture readings will occur, for instance, if a sample at a given moisture contains a (or several) large air pocket(s) for one reading and no air pockets on a subsequent reading. The finer the individual particles are that make up the sample, the smaller will be the chance of error arrising due to inhomogeneity. Note that the smallest error in two measurements of an inhomogeneous sample will occur if the sample is not moved between measurements and all readings are normalized to the initial reading. The resulting data will then show the drying curve of the sample.

IV. Experimental Procedure

In this section a description is given of the procedures and testing systems investigated in this feasibility study. A short discussion is presented on the types of foliage used in the study and also some of the experimental results are discussed when these data resulted in establishing or changing a test procedure.

The Unbalanced OWL Over a Ground Plane

A major portion of the study effort was concentrated on the OWL over a ground plane since living foliage was being tested and since it represented the original thinking behind the project. Some discussion is needed to explain why an unbalanced line over a ground plane was chosen for the study instead of the balanced two wire system used by Parkeretal. [1, 2]. This was a feasibility study which implied that all practical aspects of a given system had to be investigated. It was not known beforehand if there was an optimum frequency or height for operation of the OWL so it was desired to be able to operate with maximum flexibility with the test system. If a balanced line was used, a half wave balun would have had to be cut for each test frequency and many balun changes would have occured in the course of the study. The unbalanced line required no balun and hence was not frequency limited. The ground plane (wire mesh) was used to assure the data would be taken with respect to a known, repeatable reference plane. Without the wire mesh ground plane the variation of soil parameters could affect the results. This system also required just one conductor and hence was much easier to move to the various heights and positions used

during the study. The experiment was set up in the greenhouse facilities of the U. S. Forest Service on the Montana State University campus at Bozeman, Montana. Through this courtesy of the Forest Service, a plot of grain was grown and tests conducted under controlled conditions. Both the temperature and humidity in the test area were controlled and monitored throughout the test. The test plot was a box 5 feet by 13.5 feet with a 5 inch depth. To allow drainage of excess water, holes were drilled in the bottom of the box. The box was covered with half inch galvanized wire mesh stapled to the edges and the mesh was soldered where ever a joint had to be made. This formed the ground plane. A picture of the completed test setup is shown in Fig. 1. The figure shows the OWL mounted one inch above the ground plane, the feed point connection and ground taper, and the short circuit at the load end of the line. Figure 2 shows a closeup of the feed point of Fig. 1 illustrating the connection between the HP Vector Impedance meter, the OWL, and the ground taper. The plexiglas support for the end of the line is also shown.

The transmission line was 5/8 inch brass tubing, 11.33 feet in length. Provisions were made to adjust the line height from the position 1.25 inches above the ground plane to positions 3.25 inches or twelve inches above the plane. Originally the line was also to be moved laterally (see Fig. 1) but later tests showed this to be unnecessary. The line length was chosen such that the line would be quarter, half, three-quarters, and a full wavelength long at the resonant test frequencies (between 15 and 90 MHz). The tests were also conducted at five non-resonant frequencies; these being 15, 20, 50, 70, and 90 MHz.

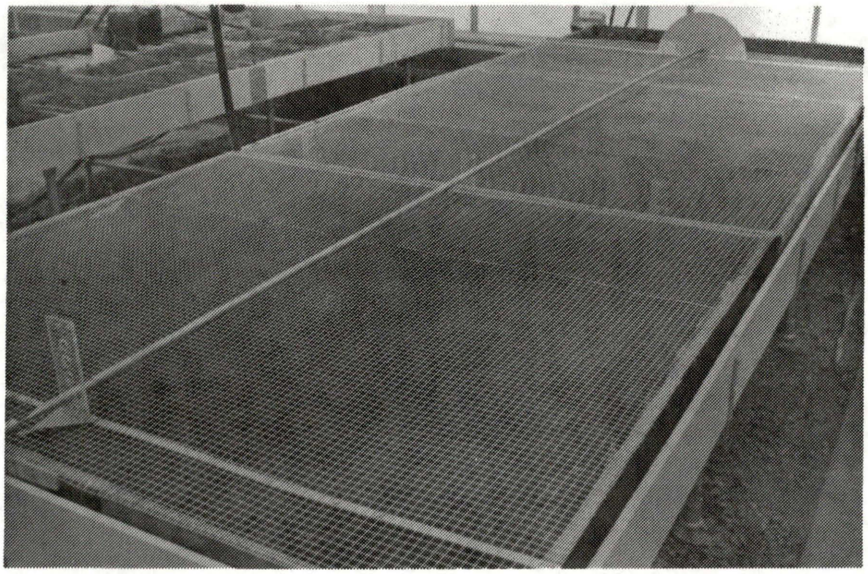


Figure 1. The OWL in place 1.25 inches above ground plane just after seed plantings in January 1970.

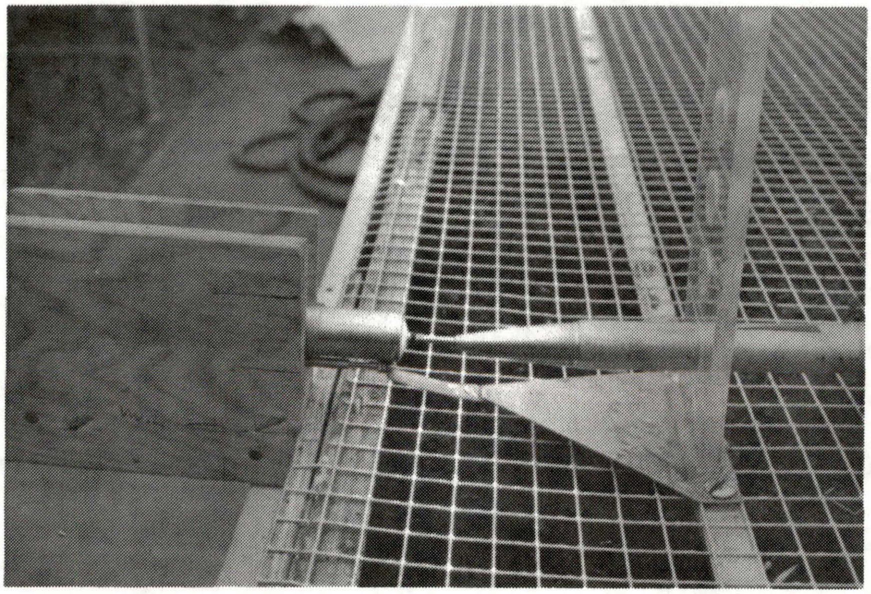


Figure 2. Closeup of OWL feed point showing the plastic 1.25 inch height line support, the ground taper for the Vector Impedance Meter probe, and the wire mesh ground plane.

The test data were taken using an HP-4815A Vector Impedance meter and an HP-5450 frequency counter to monitor the frequency. Both the magnitude and angle of the short and open circuit impedances were recorded for each line position and each test frequency. Field intensity measurements were made using a HP 608 Signal Generator to drive the line. The intensity measurements were taken every six inches along the line with a monopole first vertical and then parallel to the field lines. The line is shown set up for field intensity measurements at the twelve inch line height in Fig. 3. The foliage as shown in the picture was nearly cured as the picture was taken in July, 1970.

The test plot was divided lengthwise in three equal sections to allow three different grasses to be used. Wheat was planted on the left of the line (looking toward the termination), oats were planted in the center section and barley on the right side of the line. The seed bed was prepared by making furrows two inches apart and planting 15 - 20 seeds per foot. Water was applied to the test bed every second day starting January 19, 1970 until the plants were about one foot high. Daily watering was then used until the plants started to yellow when every second day watering was again used. In about two weeks water was applied every third day and after about one more week no water was applied to allow the plants to completely cure. Figures 4 and 5 show the stand obtained as of March 6, 1970 and Fig. 6 shows the stand in April.

Figures 4, 5, and 6 also show further details of the test plot while the test were being conducted. In Fig. 4 the line mounted at the twelve inch height can be seen as well as the short circuit used in the tests.

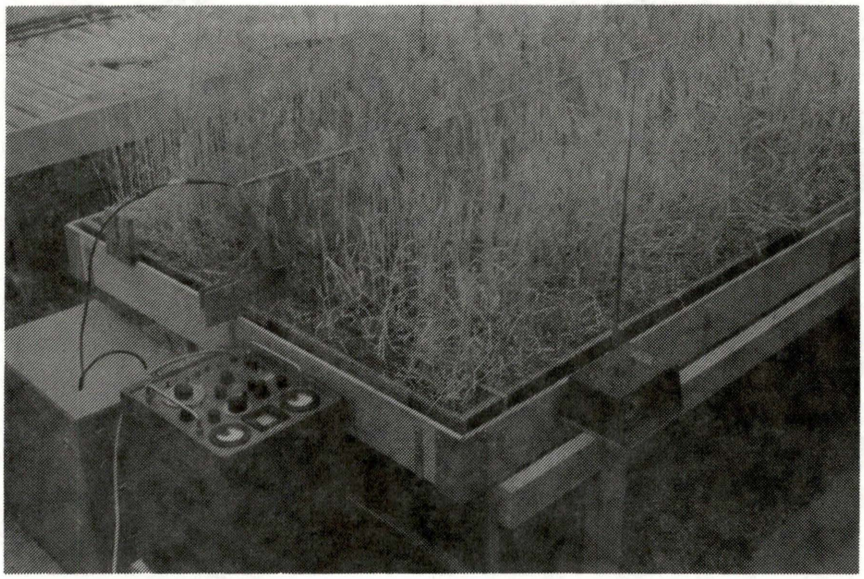


Figure 3. The OWL at the 12 inch height and test plot prepared for field intensity measurements.

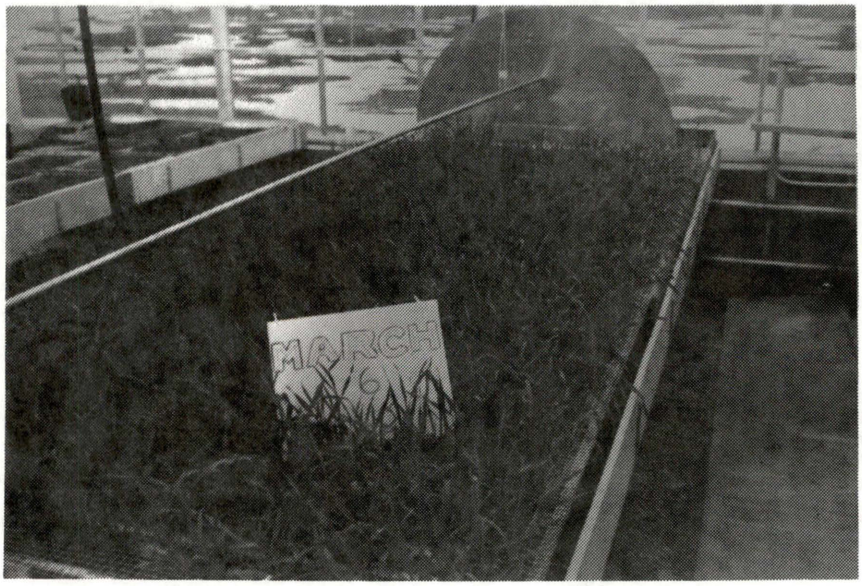


Figure 4. The test box on 6 March, 1970 showing the stand of grass obtained, the OWL at the 12 inch height, and the shorting plane.

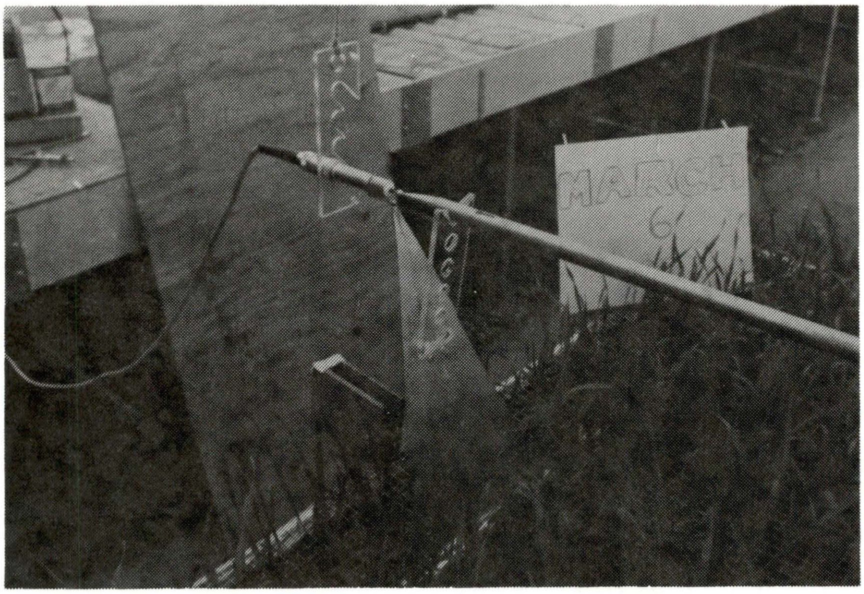


Figure 5. Closeup of the OWL feed point on 6 March 1970, showing the OWL plastic support and the ground taper for the 12 inch line height.

Figure 6. Closeup of the OWL feed point in April 1970 showing the stand of grass obtained and part of the ground taper for the 3.25 inch line height.

This short is larger than that shown in Fig. 1 since tests showed the short in Fig. 1 was not adequate. Figure 5 shows the feed and ground taper for the 12 inch height line while Fig. 6 shows the feed and part of the ground taper for the 3 inch high line.

The moisture readings for the 12 inch height were not taken from a single xyelene reading. At the 12 inch OWL height the fields tend to spread a significant distance from the OWL. As a result the field was not contained in just the oats but was also in the wheat and barley. For the 12 inch height a weighted moisture content was used. Sample foliage from the oats, barley and wheat was obtained and a xyelene test run on each sample. The moisture the OWL was sensing was then calculated by adding the wheat and barley percentages plus twice the oats percentage and dividing the result by four. In this way the oats moisture content received twice the weight of the other two grain moisture contents. Field intensity checks and calculations indicated this should be a reasonable weighting system since about half the field was in the oats with the rest in extending to the barley and wheat.

<u>Balanced Open Wire Lines Surrounded by Test Boxes</u>

Three types of OWL test boxes were studied. The first was a wooden box with a balanced two wire line extending through the box. Provisions were made at the load end of the line to allow a 12 inch by 12 inch short circuit or an open circuit to terminate the line. This test box was discussed by Gerald Gasvoda in a report submitted on March 9, 1970. The box was a 25" cube with two number 23 copper wires spaced

six inches apart and running through the center of the box to form the transmission line. The OWL was run balanced by cutting a half wave balun (operating frequency 58.2 MHz) to transform the six inch spaced OWL to RG 55 A/U coaxial cable. The parameters measured on this circuit were either the parallel resistance and capacitance using a Boonton Impedance Bridge, or the input impedance using an HP-4815A Vector Impedance meter. To keep the foliage under test from shorting the transmission line, each line was surrounded with a one inch diameter glass tube. The OWL in this box was purposely chosen to be one eighth wavelength long at the operation frequency and hence non-resonant.

The testing procedure was to obtain a reading from the Boonton Bridge or HP meter with the box empty and then a reading with the box filled full of the foliage under test. Data were taken for different weights of equal moisture content foliage as well as data on samples that had different moisture content with each sample filling the box.

A second wooden box was made to test sagebrush moisture content. This box, shown in Fig. 7, measured 39 inches long by 27 inches wide by $18\frac{1}{2}$ inches deep. The transmission lines were formed by five-eighths inch outside diameter brass tubing, 39 inches long and separated by six inches. The length of the box was chosen to be half wavelength at the design frequency of 100 MHz. A half wave balun was also used with this box with the balun cut for 100 MHz. The balun actually tuned out at 97.8 MHz and hence the tests were run at this frequency. As before provisions were made to allow the line to be terminated in an open circuit or a short circuit. The sagebrush was

Figure 7. Picture of the balanced OWL and test box used for the sagebrush experiments.

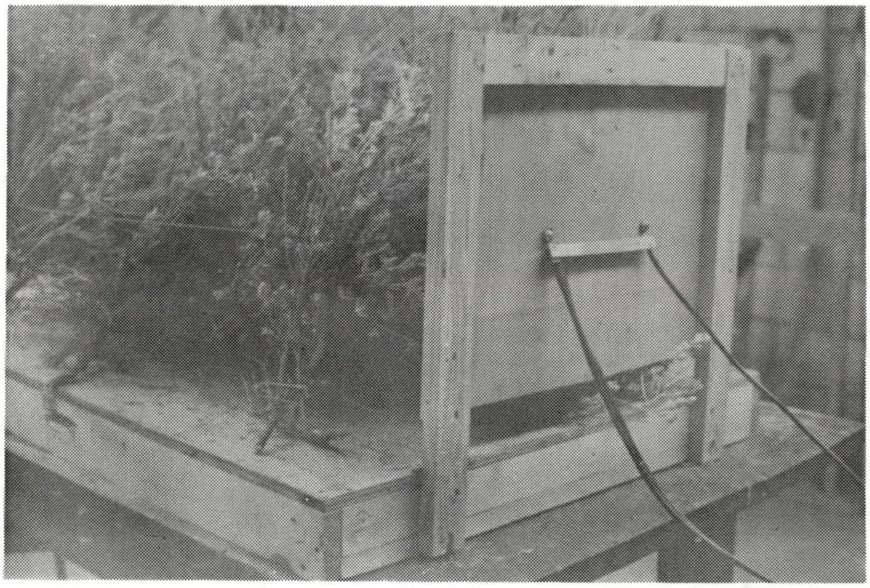


Figure 8. Closeup of the feed point of the sagebrush test box with the brush in place.

brought in from the field and after an "empty" set of readings was taken on the test box the brush was placed in the box around the OWL. The heavy main stem of the brush was placed below the OWL as shown in Fig. 8 with the leaves and smaller stems being placed up in the box and around the transmission lines. A xyelene test was run on a sample of brush to determine its moisture content and then a set of open and short circuit readings were taken. The brush was not moved after the initial reading but each day a new xyelene sample was taken to determine the present brush moisture and another set of RF data was also taken. In this way a curve of RF readings versus moisture in the brush was obtained that was fairly independent of the bulk density of the brush. The brush did tend to shrink some as it dried, which did allow some error due to the change in volume occupied by the brush.

The third test box used gradually evolved through testing from a wooden box similar to the above boxes to a short box made from one eighth inch plexiglas. The wooden box initially was constructed by modifying a very early test box. The test box dimensions after the first modification were 25 inches long by 10 inches wide and deep. The transmission lines were number 23 copper wires spaced three inches apart and 25 inches long. Previous tests had shown the necessity of keeping the foliage from either touching or getting between the wires so a four inch inside diameter PVC* plastic pipe was placed over and centered on the wires. Tests were run with this box using clipped lawn grass with moisture content ranging from 100% to 300%. The open

*Poly Vinyl Chloride

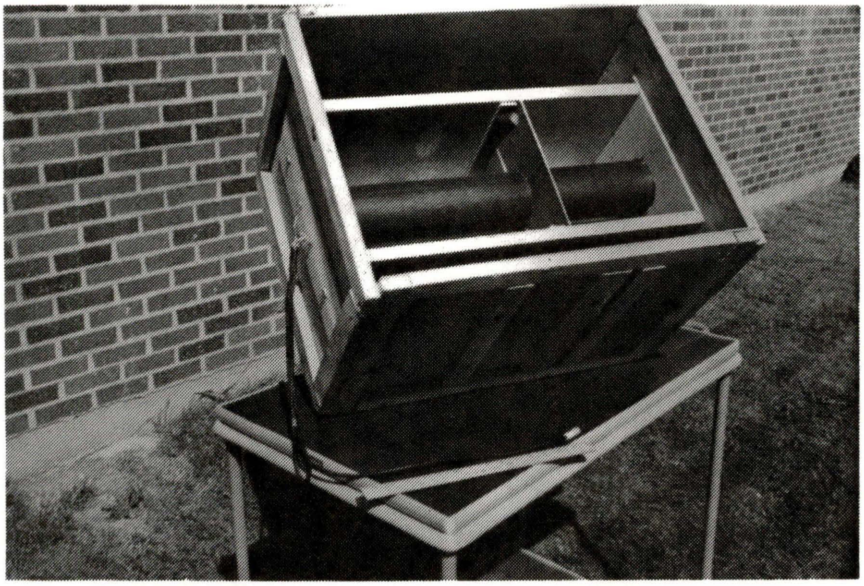


Figure 9. Picture of the modified wood test box showing the balun and feed point of the OWL and the PVC cover around the line.

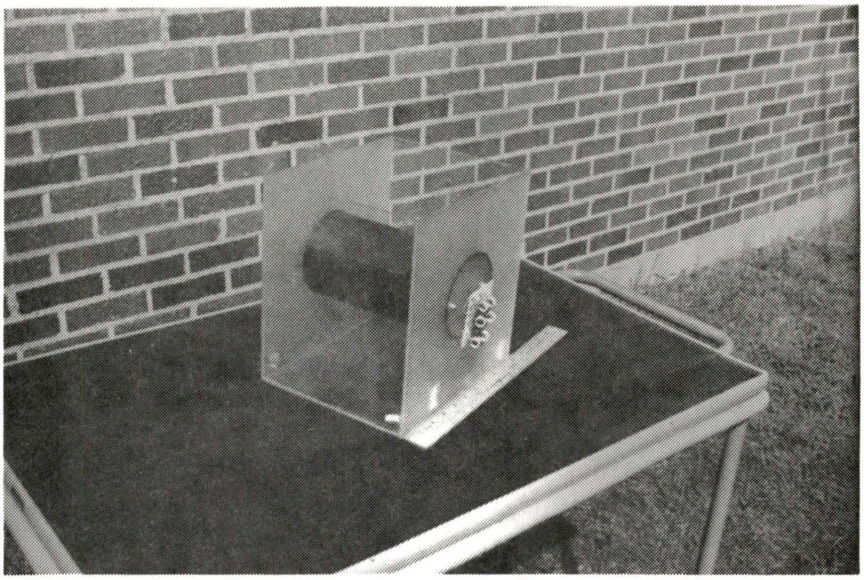


Figure 10. The plexiglas test box showing the PVC cover around the OWL and the balanced termination in place at the load end of the line.

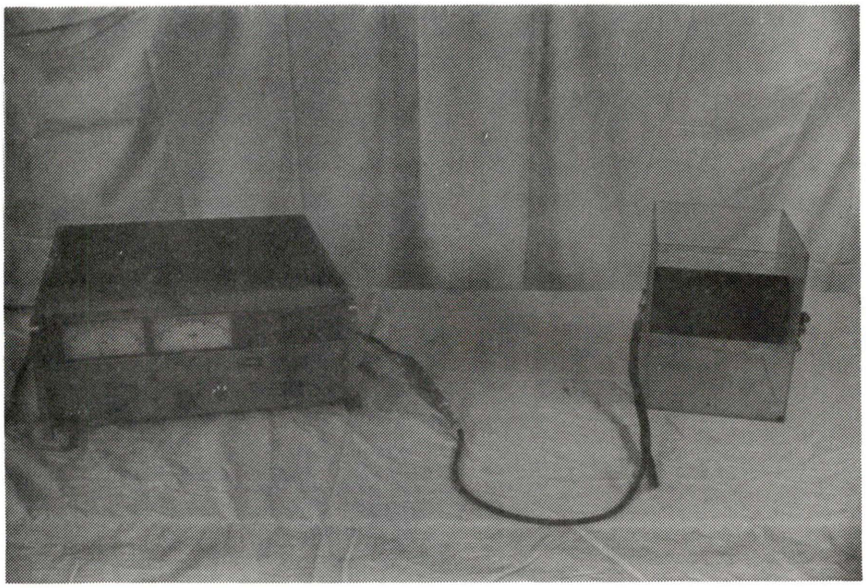


Figure 10a. The box test circuit showing the Vector Impedance Meter.

and short circuit impedance readings using the HP 4815A Vector Impedance meter indicated that only the portion of the OWL near the open circuited end of the line was sensing the grass. Hence the test volume was shortened gradually through a series of tests until it was a 10 inch cube. The line, however, was kept at the same length. A picture of the box with the final test volume is shown in Fig. 9. It was noted during these tests that the sides and bottom of the box showed considerable moisture absorption during a set of tests. Hence the final test volume was enamal painted to reduce the moisture absorption of the wood. Even this did not prove entirely satisfactory so a test volume was constructed from the one eighth inch plexiglas.

The plastic box is shown in Fig. 10 with Fig. 10a showing the plastic box in the test setup. The box was made 10 inches high and wide and 8 inches long. The transmission lines were number 23 copper wire again covered by the four inch PVC plastic pipe. The plastic box and the final version of the wood box discussed in the previous paragraph were both operated with a half-wave balun cut for 108 MHz. As will be discussed shortly this was not the frequency at which the tests were performed. Note that a major difference exists between the final test volume in the wood box and the plastic box; the transmission line was only 8 inches long in the plastic box. When the box was constructed the reasoning was that the extra 17 inches of OWL in the wood box was not necessary and hence was not included in the plastic box. Measurements showed that the sensitivity of the plastic box to moist grass was very much less than the wood box, however. Hence a

termination consisting of lumped inductors and capacitors was designed and used during the tests. The first termination used is shown schematically in Fig. 11a while a second circuit used later is shown in Fig. 11b. These terminations approximated a length of open-circuited line and when used with the plastic box brought the sensitivity of the box above that of the wooden box.

The frequency of operation of the modified wooden box and the plastic box with the terminations was not the design frequency of the balun. When a particular box was operated at the balun frequency very little sensitivity to a change in the dielectric surrounding the line was observed. It was felt that most of the electric field was being concentrated so near the OWL that there was only a very weak field in the foliage. Hence only a very small change was registered from an empty box to one filled with foliage. Experimentation showed there was a highly sensitive frequency, however. The HP impedance meter was tuned downward in frequency while connected to an air-filled box and the expected maxima and minima occurred. It was found for the plastic box that the frequencies of 57 MHz for the symmetric termination and 56 MHz for the non-symmetric were maximum impedance points with a zero phase angle. There was good sensitivity to dielectric change at these points. For the wooden box a similar impedance point was found for a frequency of 101 MHz. The tests were run at these frequencies. A minor difficulty in running the tests in this fashion is that the OWL is being run unbalanced. This means that one of the lines is receiving more energy than the other which implies

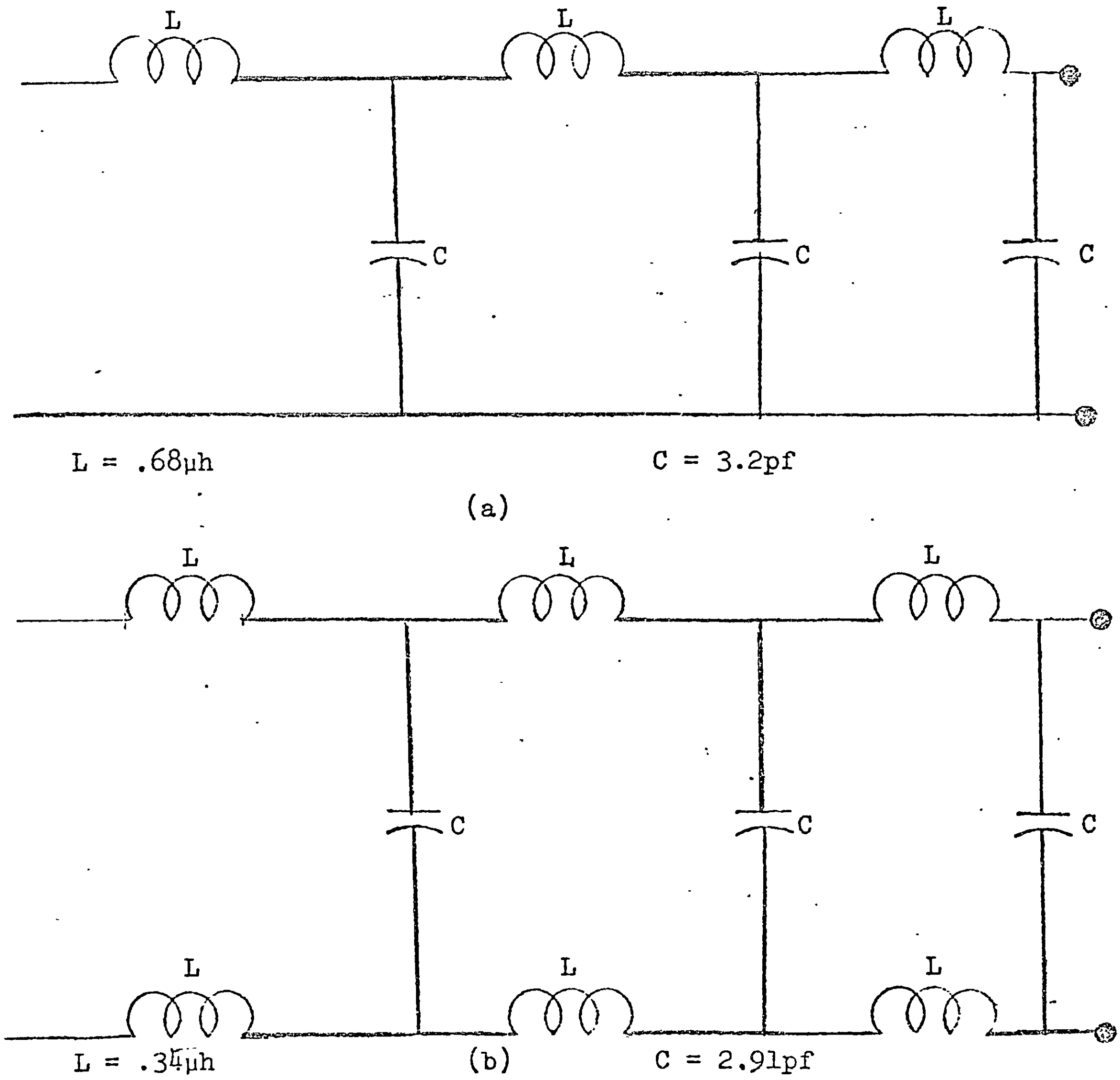


Figure 11. Terminations used in conjunction with the plastic box: (a) unbalanced, (b) balanced.

a non-symmetric distribution of the electric fields about the OWL. An actual design of one of these test boxes would include correcting the situation to operate the OWL as a balanced system.

200 MHz Coaxial Cavity

As explained previously the half wave length cavity could not be used in the manner for which it was designed since the moisture in the grass caused too much loss in the cavity. Putting it another way, the wet grass had such a high loss tangent that no measurable signal could be coupled out of the cavity when it was full of grass. Hence the experimental procedure was modified slightly and only part of the cavity was filled with the foliage to be measured. For the RF power level and detector sensitivity available, the optimum depth was found to be three inches. That is, three inches of the end of the cavity was filled with grass while the rest remained filled only with air. The measurement setup is shown in block diagram form in Fig. 12 and a photograph of the setup in Fig. 12b.

The test procedure was to measure the resonant frequency, the frequency at which maximum power was indicated on the meter, and the two frequencies where the power indicated on the meter was less than the maximum by 3 db. The Q of the circuit was then calculated from equation (20). This procedure was applied to a number of clipped lawn grass samples of various weights and various moisture content.

The cavity itself was a coaxial cavity operating in the Transverse Electro Magnetic (TEM) mode at a design frequency of 200 MHz. The actual operating frequency (air dielectric) turned out to be 199.589 MHz

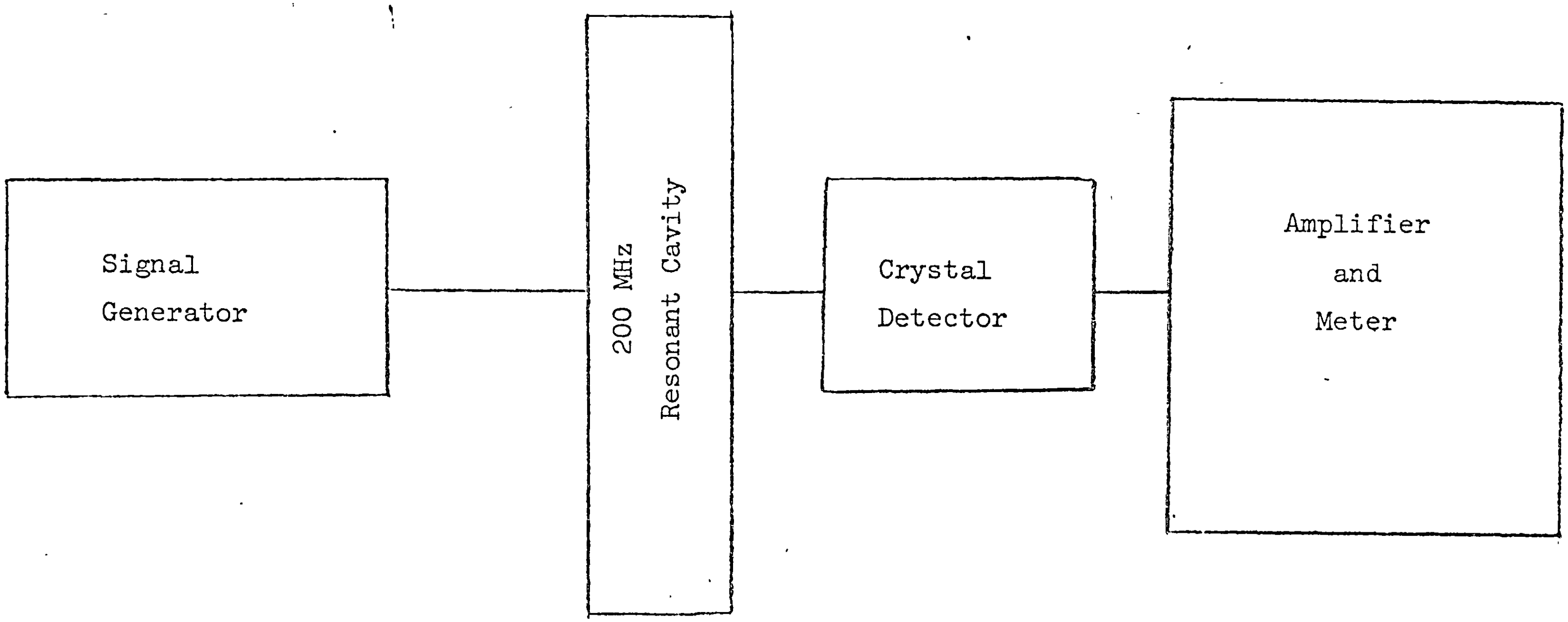


Figure 12a. Block diagram of the 200 MHz resonant cavity test circuit.

Figure 12b. The 200 MHz cavity test setup showing from left to right: the signal source, the 200 MHz coaxial cavity, the crystal detector, and the amplifier and meter.

with a Q of 1600. The dimensions of the cavity were

L = length = 29.6 inches

inside diameter of outer conductor = 3.8 inches

outside diameter of inner conductor = 1.75 inches

These dimensions resulted from using 4 inch aluminum irrigation pipe and 1.75" aluminum conduit. The resulting impedance was 47 Ω (air dielectric) and hence matched the 50 ohm feed cable well. One end of the cavity could be unscrewed to allow the sample to be placed in the test volume. The cavity was probe coupled at the maximum electric field point. That is, the probes went through the cavity outer conductor along a diameter at L/2. The probes were simply the center conductor and dielectric sheath of a length of RG 55A/U coax cable. The outer conductor of the cable was soldered to the outer wall of the cavity. A picture of the cavity showing the probe connections; inner and outer connectors, and the end plates is shown in Fig. 13. To keep a constant test volume, a styrafoam ring was cut that fit tightly to both the outer and inner conductors. This was fixed at the 3 inch depth (measured from the end of the cavity). The styrafoam is nearly lossless at 200 MHz and has a dielectric constant that is nearly that of air. Hence its presence in the cavity did not affect the Q readings.

The 10 GHz Attenuation Test Circuit

Basically the 10 GHz test circuit consisted of a 10 GHz source, a precision calibrated attenuator, two x-band horn antennas, the test volume, a detector, and an amplifier and meter. A block diagram of the circuit is shown in Fig. 14.

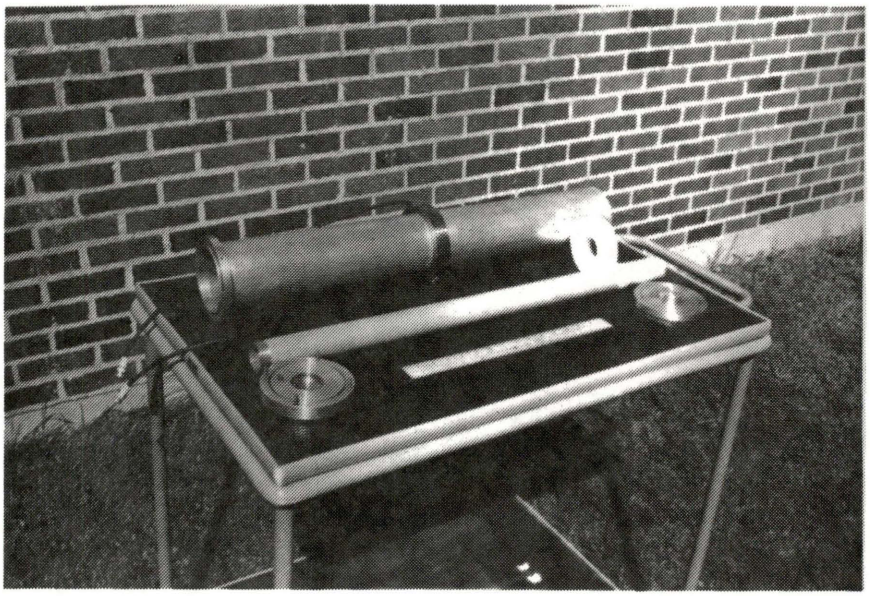


Figure 13. Picture of the pieces making up the 200 MHz coaxial cavity. Top to bottom: the outer conductor with both probes attached, polyfoam ring, inner conductor, and the two end caps.

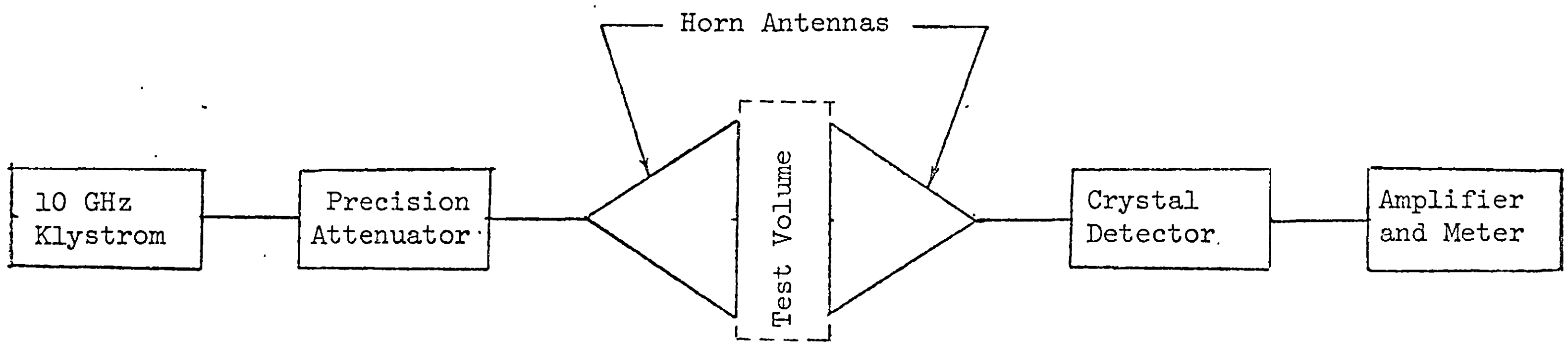


Figure 14. Block diagram of the 10 GHz test circuit.

Due to the short wavelength at 10 GHz the above circuit could probably be designed to be the smallest of any of the test circuits discussed in this report.

The test procedure was to fill a small box made of one-eighth inch thick plexiglas (or a combination of the plastic and one sixteenth inch thick aluminum) with the material to be tested and insert the box between the two horn antennas. As discussed in section II the moisture in the sample caused some of the microwave energy to be absorbed in the material and lost as heat. A direct measure of the power loss was obtained by removing attenuation from the circuit with the calibrated attenuator until the meter indicated the same value of power as obtained with no foliage in the test volume. As the moisture in the foliage was changed a curve of attenuation in db (decibels) versus moisture was obtained. The measurement procedure was therefore quite simple requiring only that a test box be filled and inserted and the attenuator dial moved to re-zero the meter.

Several test volumes (boxes) were investigated to ascertain if the circuit's sensitivity to bulk density could be decreased and also to see how the attenuation vs. moisture curves were affected by the test volume. Of the four test cells used, two were all plastic boxes and two were metal on four sides with plastic (plexiglas) windows through which the 10 GHz beam passed. The four test volume dimensions were:

A)	2.75" long x 2" wide x 2.4" deep	(all plastic)
B)	3.75" long x 1" wide x 3.55" deep	(all plastic)
C)	2.65" long x 2" wide x 2.4" deep	(4 sides metal)
D)	2.75" long x 1" wide x 2.35" deep	(4 sides metal)

A picture of the boxes is shown in Fig. 15 while Fig. 16 shows box number C in place between the horn antennas in the 10 GHz setup.

It was found during the course of testing foliage in the test cells that the way the test volume was filled made a significant difference in the repeatability of any particular attenuation measurement. The foliage used in the 10 GHz test circuit was mown lawn grass since grass clippings fit into the 10 GHz test volumes without further chopping or cutting. The studies showed that if the grass was placed into a test volume so that the box was filled at right angles to the direction of propagation, a large repeatability error occurred when testing the grass samples. If the test volume was filled so that the box filled in the direction of propagation the repeatibility error was significantly reduced. Hence filling the test volume in the latter manner became part of the experimental procedure.

Types of Foliage Studied

The foliage studied has been mentioned before but will be discussed in more detail in this section. The foliages used in the study were whole sagebrush plants (cut off at ground level), cut alfalfa hay, growing wheat, oats, and barley plants, and cut lawn grass. The alfalfa hay was used in some of the first experiments since it was felt to be representative of heavy grass or small twigs such as might be encountered in field operation of the moisture sensing circuit. The hay also could be obtained while still green (and hence having a high moisture content) and measured with the RF circuit while it dried. The hay was

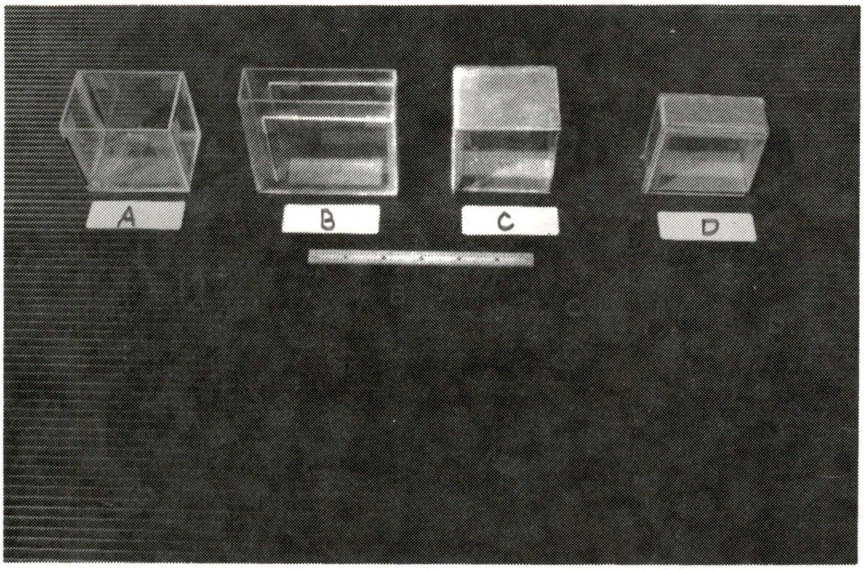


Figure 15. The four test boxes used in the 10 GHz test circuit.

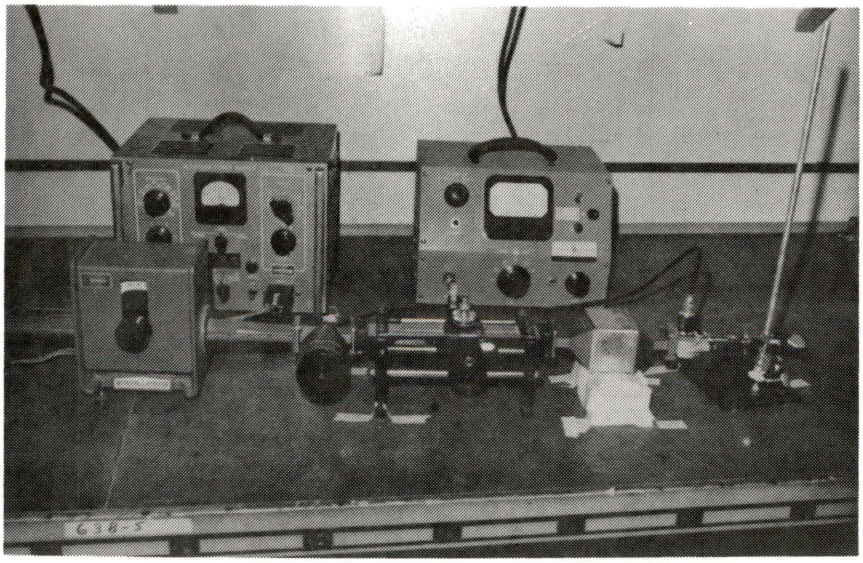


Figure 16. The 10 GHz test circuit showing test box (c) inserted between the two 10 GHz horn antennas.

used to check out the first OWL in a test box and the first test results were reported by Gerald Gasvoda in his report of March 9, 1970. A drawback found with the hay was that as it dried it was very prone to dropping the leaves from the stems of the plants. The result was that during the course of an experiment (several days) more and more of the leaves ended up on the bottom of the test volume leaving mostly stems around the most sensitive parts of the OWL. This adversely affected the accuracy of the results.

Shortly after the studies of the alfalfa hay were completed the sagebrush plants were put on test. These plants were placed in the test volume with the heavy stem down and the smaller stems and leaves around and over the line. After the test volume was filled with the brush, xyelene tests and RF tests were made without disturbing the plants. The sagebrush held its leaves much better as it dried and hence the only changes sensed by the RF were moisture changes and bulk density changes due to the shrinkage of the sage as it dried. The latter appeared visually to be quite small.

Much of the testing done on the various open wire lines surrounded by a test volume was done with freshly clipped lawn grass. It was felt this was relatively near to a field type grass and was easily obtained in large quantities. The lawn grass used also showed a wide moisture range particularly if it was obtained just after a rainstorm. Fresh mown grass cut within 5 to 8 hours after a typical half inch rainstorm tested above 400% moisture content. After a week of no rain, fresh mown grass from the same lawn was typically

250% to 300% moisture content. A grass sample could also be dried overnight at room ambient in the lab to obtain samples with less than 10% moisture. Thus the lawn grass offered good quanity, wide moisture range, and easy access. It was also established in the study that it offered a very wide range of bulk density variation as the grass varied from very wet to very dry.

The growing small grain plot offered the nearest approach to actual field foliage such as cheat grass. Even though three grain types were available to study, (oats, barley, and wheat) testing demonstrated the OWL was not sensitive to the different types of plant. The test plot was followed from sprouting through harvesting during this study, thus giving a set of OWL data for all stages of growth. The moisture in the plants at any particular time was obtained by xyelene treatment of statistically selected leaves and stalks of plants taken from the test plot. Care was taken to achieve a statistically valid sample and to not invalidate the RF test results by over sampling at any one spot.

Other materials that received limited study were small grains including oats, barley, corn, soy beans, and wheat tested in the 10 GHz circuit. These materials were used primarily to see if this test circuit could be expected to perform in a similar manner as with the foliages mentioned. The test did show a linear change in attenuation with moisture. This will be further discussed in the concluding section after the data is presented.

V. Experimental Results

The data obtained from the various test circuits are presented and discussed in this section. A large amount of data were taken and analyzed with the data presented in this section considered to be representative of the trends observed in the data for a particular test circuit.

The Unbalanced OWL Over a Ground Plane

The line was operated both resonant and non-resonant as pointed out in the last section. Hence the data will be presented and discussed in these same two sections.

A. Non-resonant frequency data. The first plots shown, Figs. 17 and 18, illustrate the measured relationship between the magnitude of the short circuit impedance and the moisture content of the growing grain. These points were obtained with the line 3.25 inches above the ground plane. Notice that for 30 and 70 MHz the impedance is high for low moisture content and moves lower as moisture increases. At 15, 50, and 90 MHz the opposite trend is noted. This is to be expected for the following reason. At 30 and 70 MHz the line is respectively about three-eighths and seven-eighths of a wavelength in length while at 15, 50, and 90 MHz it is close to one, five, and nine-eighths of a wavelength. As the moisture increases it is expected that the dielectric constant of the foliage will increase, thereby causing the wavelength to decrease since for the TEM mode

$$\lambda = \frac{3\text{x}10^8 \text{ meters/sec}}{f\sqrt{\varepsilon_r}} \qquad (29)$$

where f = frequency

ε_r = relative dielectric constant

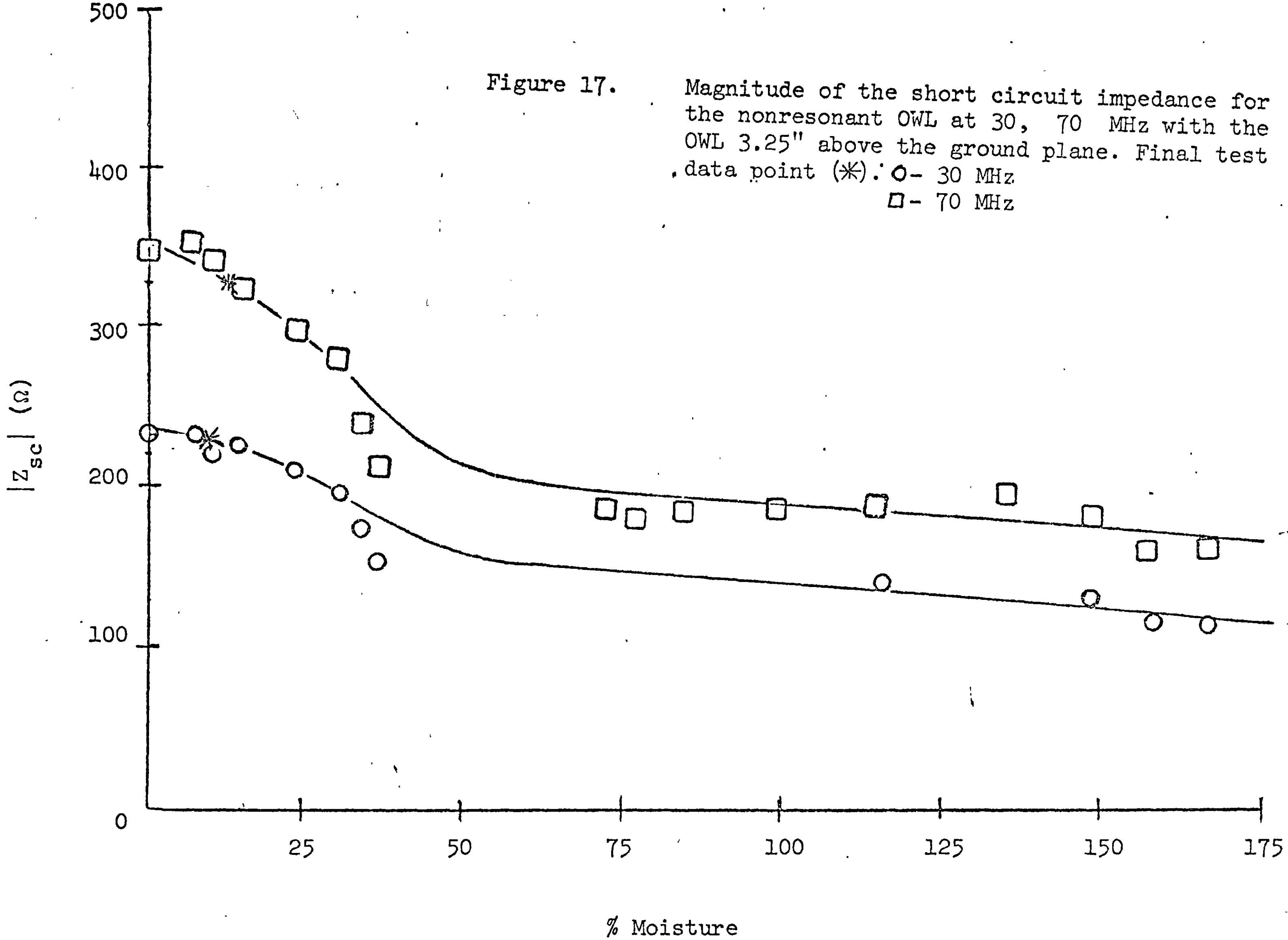


Figure 17. Magnitude of the short circuit impedance for the nonresonant OWL at 30, 70 MHz with the OWL 3.25" above the ground plane. Final test data point (✳). O- 30 MHz □- 70 MHz

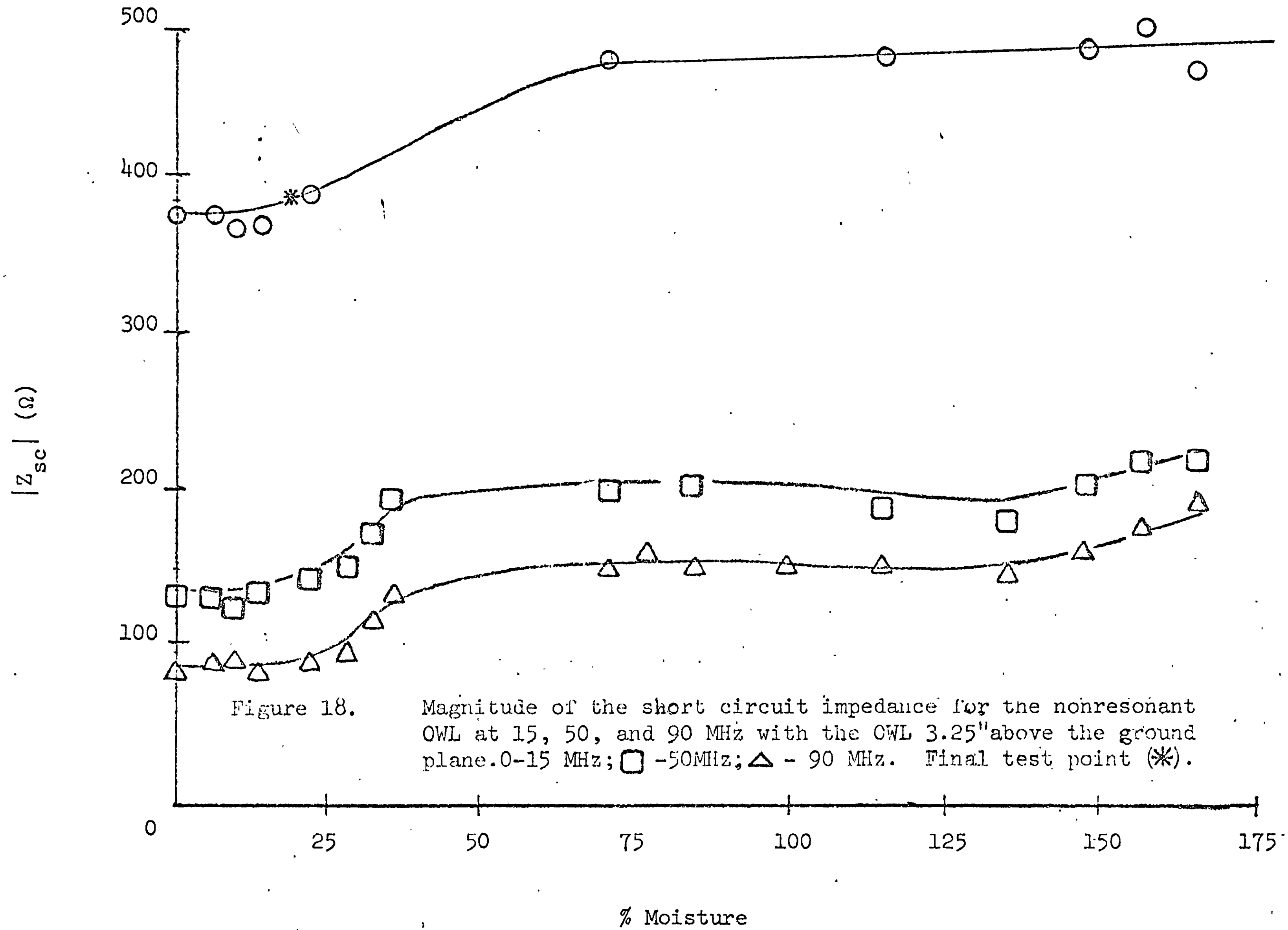


Figure 18. Magnitude of the short circuit impedance for the nonresonant OWL at 15, 50, and 90 MHz with the OWL 3.25"above the ground plane. ○-15 MHz; □ -50MHz; △ - 90 MHz. Final test point (✱).

For a line that is 3, 7, 11$\cdots$ $\lambda/8$ long the short circuit impedance will decrease as the line gets electrically longer (λ decreases) but for 1, 5, 9, $\cdots$ $\lambda/8$ the short circuit impedance will increase as the line gets electrically longer. Exactly the opposite effect should be observed for the open circuit impedances. That is, for 30 and 70 MHz Z_{op} should be low at low moisture and increase while for 15, 50, and 90 MHz it should start high and decrease. This is observed in Fig. 19.

The Z_{sc} curves in Figs. 17 and 18 do indicate a change in Z_{sc} with increasing moisture. The slopes of the curves are rather flat, however, except in the range of 0 to 75% for 30 or 70 MHz. A special point marked by a (✻) sign is shown on the curves in Figs. 17 and 18. The final experiment performed before the grains were cut was to give the test plot one final, heavy watering. The idea was to simulate a heavy rain on grass that was nearly cured to see if the OWL would sense any moisture increase in the foliage. Before the watering the oats showed only 6% moisture (xylene test). The morning after the watering the oats showed 16% moisture in a xylene test. The (✻) marks on Figs. 17 and 18 show the readings obtained with the OWL. Reading the moisture from the curves of Fig. 17, for instance, the OWL determined moisture read 12% on the 30 MHz curve and 13% on the 70 MHz curve. This special test point is also shown on several of the figures following 17 and 18.

Consider Figs. 19 and 20 now. Fig. 19 shows the variation of Z_{op} with moisture content for the OWL 3.25 inches above the ground plane while Fig. 20 shows the Z_{op} variation at 50 MHz at 1.25, 3.25, and 12 inches above the ground plane. Nearly the same variation is observed as the Z_{sc}

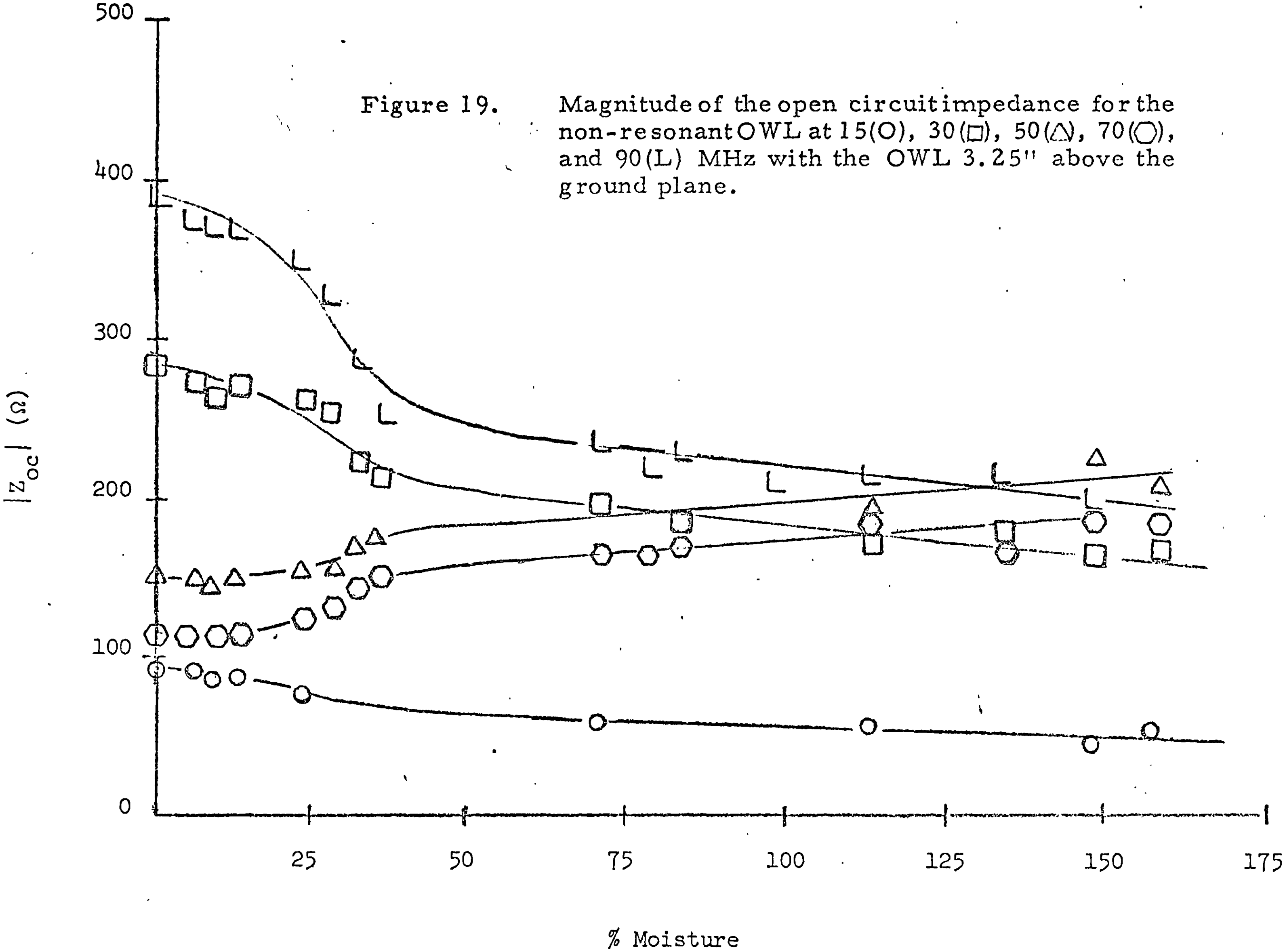


Figure 19. Magnitude of the open circuit impedance for the non-resonant OWL at 15(O), 30(□), 50(△), 70(⬡), and 90(L) MHz with the OWL 3.25" above the ground plane.

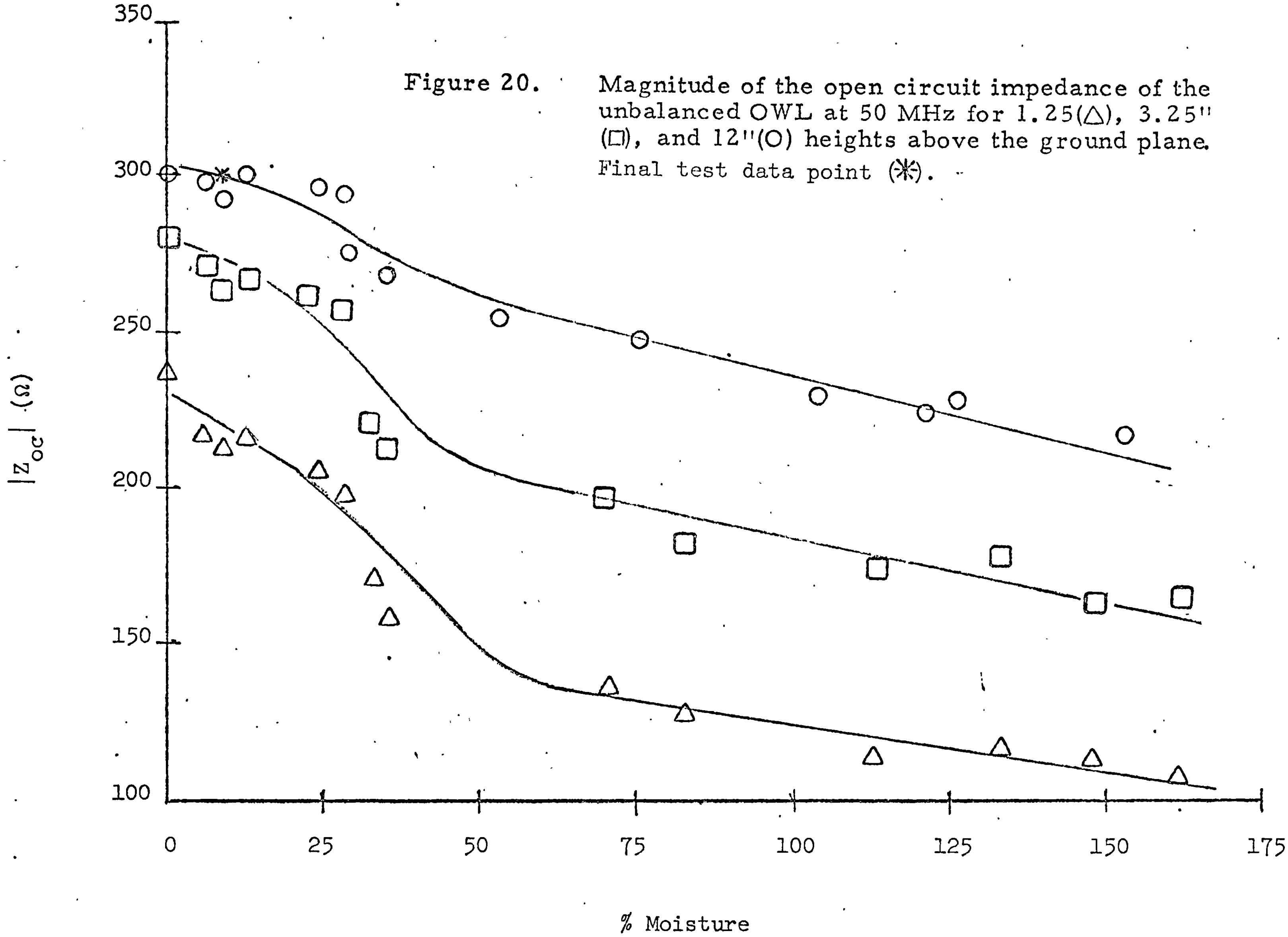


Figure 20. Magnitude of the open circuit impedance of the unbalanced OWL at 50 MHz for 1.25(△), 3.25" (□), and 12"(O) heights above the ground plane. Final test data point (✳).

(except for the expected curve inversion) but Z_{op} at 50 MHz retains more slope at the higher moistures. It is seen in Fig. 20 that one could read out to 175% moisture content with the greatest expected accuracy occurring in the 0 to 75% range. The curve reflecting the greatest change in Z_{op} with moisture is 50 MHz with the OWL 1.25 inches above the ground plane.

A typical measured phase angle plot for Z_{op} (Z_{sc} is similar) is shown in Figure 21. These data are the phase angles versus moisture read with an open circuit termination with the line 3.25 inches above the ground plane. The angles approach $+90^{o}$ or -90^{o} depending on whether the line is 3, 7, $\cdots$ $\lambda/8$ long or 1, 5, 9, $\cdots$ $\lambda/8$ long. The general shape of the phase curves is the same as those of the magnitude curves. Again a rather small slope is observed making accurate reading of the curves questionable for a moisture sensing system.

As indicated in the analysis section, the square root of the product of the open and short circuit impedances is the characteristic impedance of the line. One might expect Z_o to remain fairly constant after considering the above relationship and Figs. 17-20. Figure 22 shows that indeed the magnitude of Z_o does remain nearly constant with changing moisture while Fig. 23 shows the change in phase angle of Z_o with moisture. Note that while the slope of the phase angle curve looks fairly large that the total change from 0 to 175% is only 10^{o} at most. Note also that the 1.25 inch height curve is the most "well-behaved" of the three heights. This trend for the 1.25 inch height to be the best curve is seen also in most of the other data that will be presented in this section. The sensing fields are the most confined in the area of the OWL at 1.25 inches and hence less sensitive to errors introduced by objects external to the grass being measured.

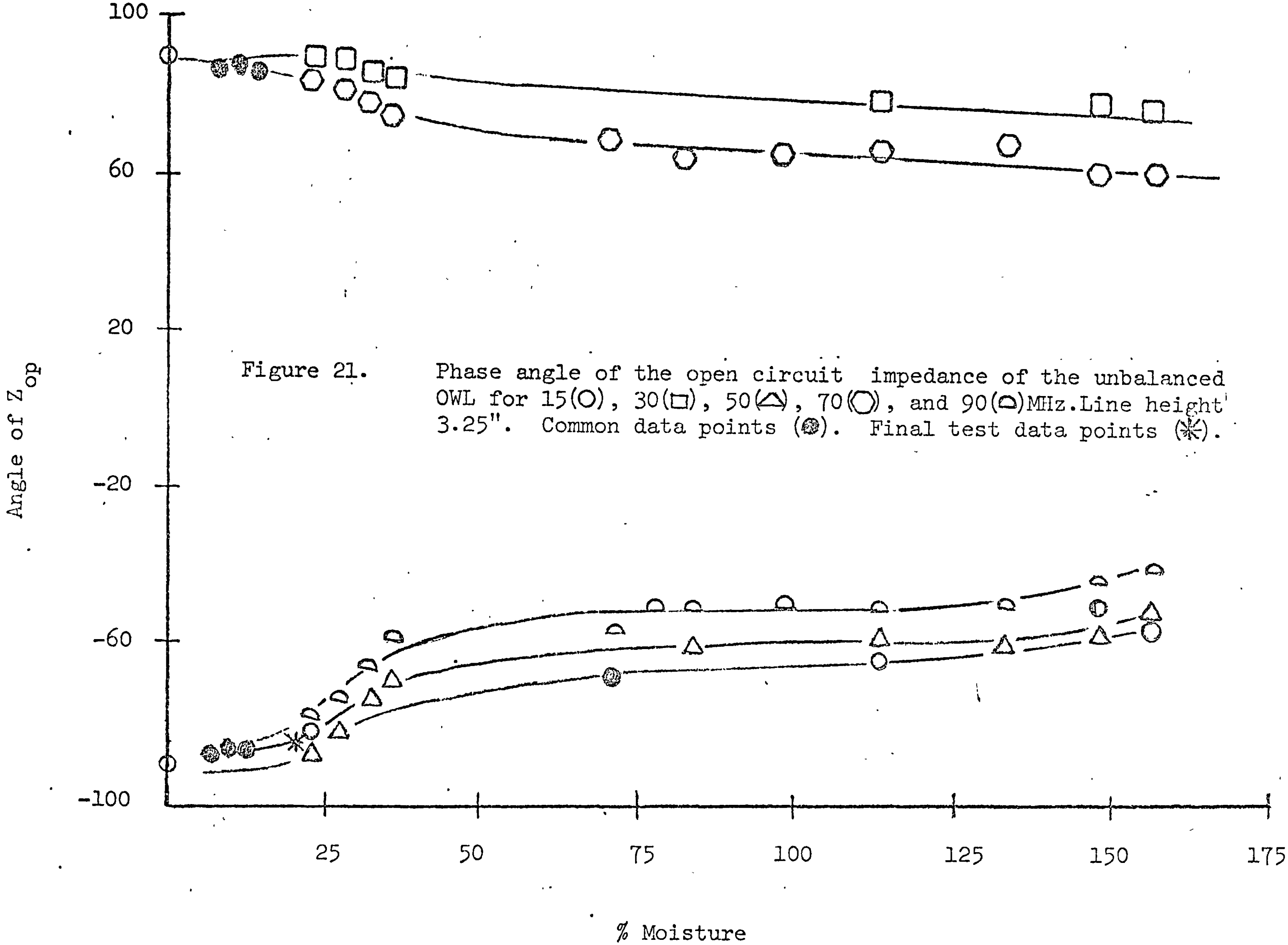


Figure 21. Phase angle of the open circuit impedance of the unbalanced OWL for 15(○), 30(□), 50(△), 70(⬡), and 90(⌓)MHz. Line height 3.25". Common data points (●). Final test data points (✳).

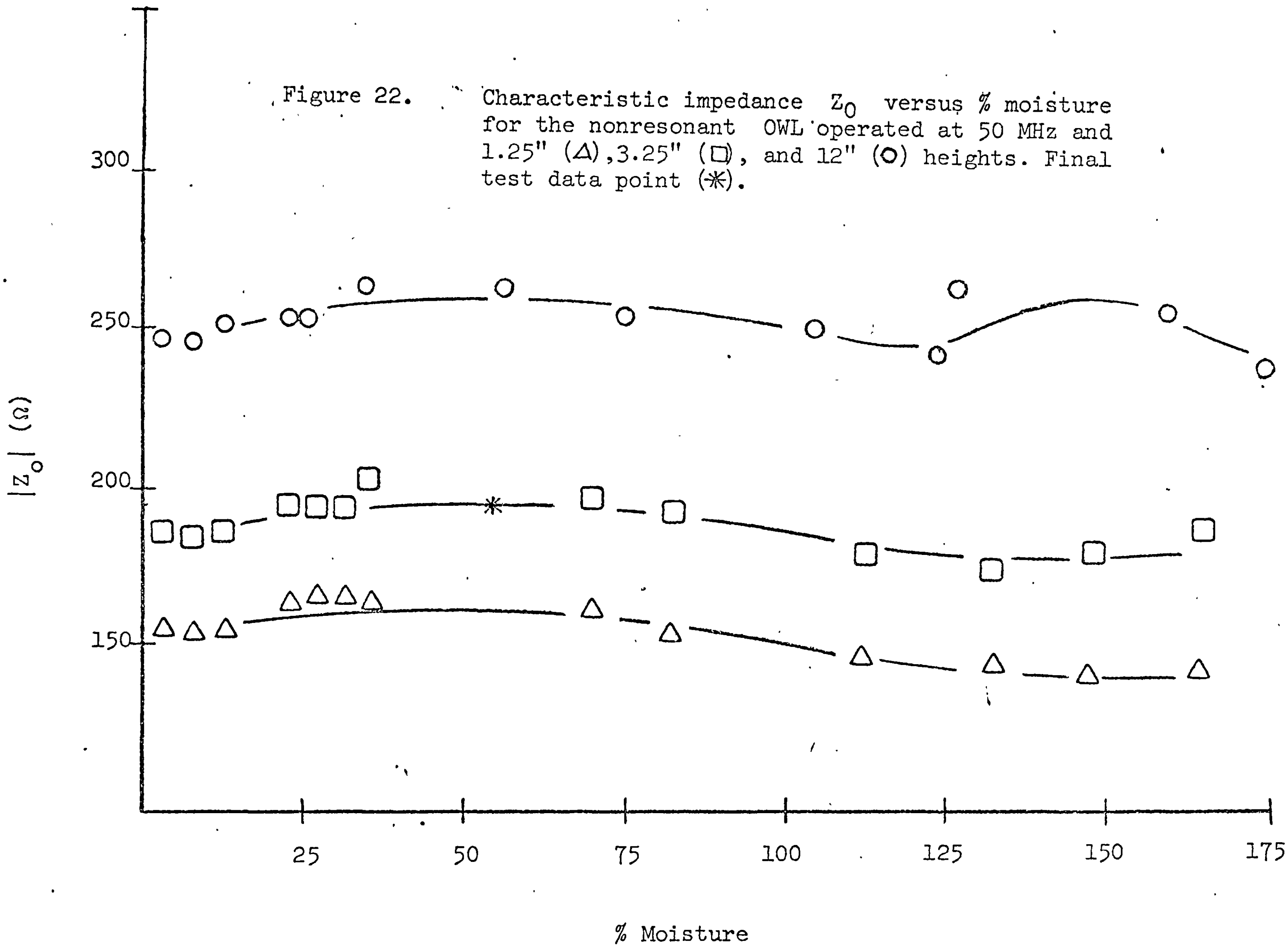


Figure 22. Characteristic impedance Z_0 versus % moisture for the nonresonant OWL operated at 50 MHz and 1.25" (△), 3.25" (□), and 12" (○) heights. Final test data point (✳).

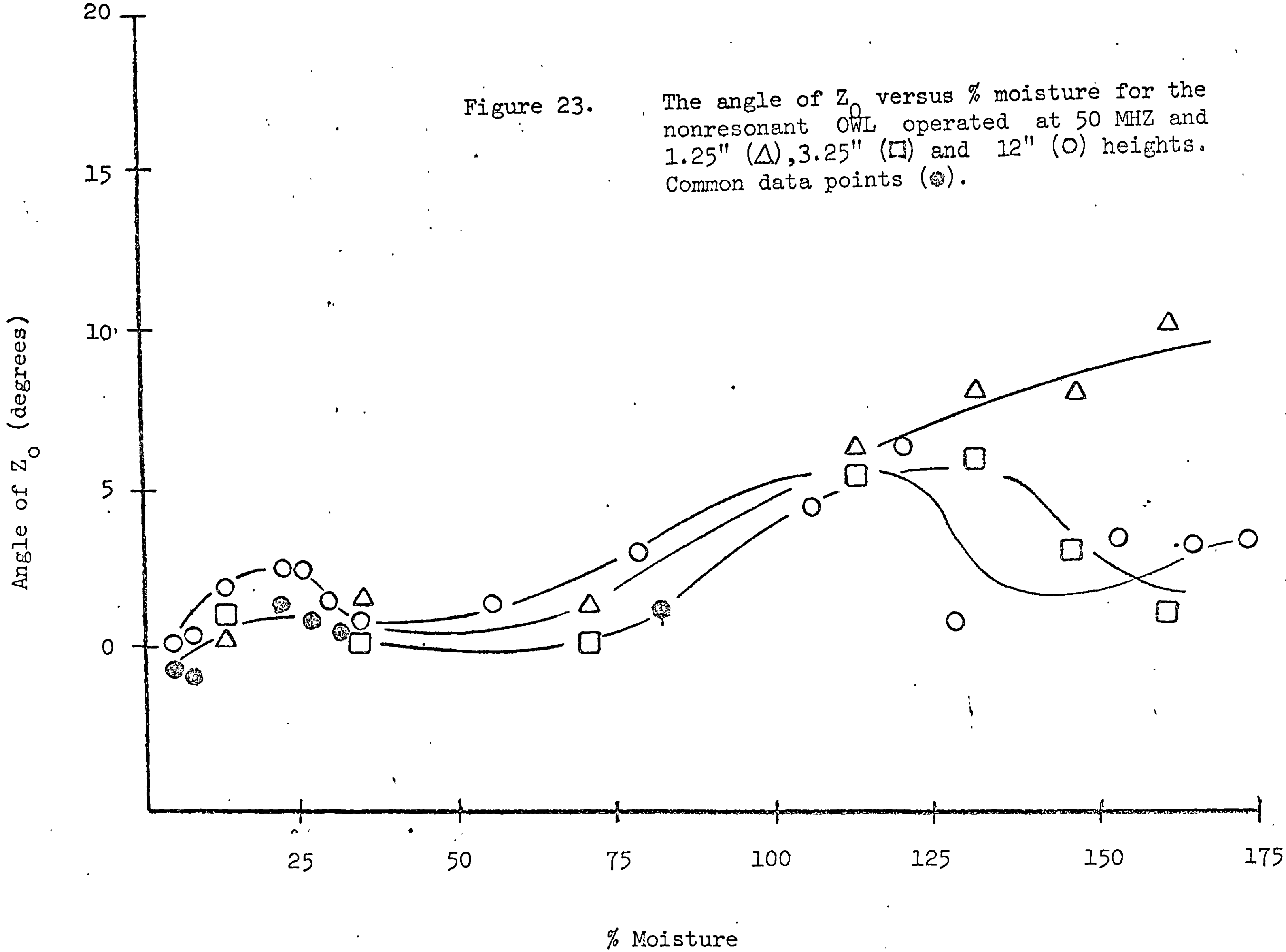


Figure 23. The angle of Z_o versus % moisture for the nonresonant OWL operated at 50 MHZ and 1.25" (△), 3.25" (□) and 12" (○) heights. Common data points (◍).

The secondary parameters calculated from Z_{op} and Z_{sc} are the conductivity (σ), the loss tangent (δ), the attenuation constant (α), and the relative dielectric constant (ε_r). The measured data was fed into the computer and the resulting runs examined as to the above parameters. The typical plots of these calculated parameters are shown in Figs. 24 through 27. The frequency of 50 MHz appeared from the data to be the best frequency for sensing the moisture. Note again that the 1.25 inch height data is the most well-behaved. The loss tangent curve of Fig. 25 shows the most sensitivity with an order of magnitude change being observed in δ as the moisture changed from 0 to 175%. It is seen in Fig. 27 that the curves of calculated ε_r show the 1.25 inch height curve again to be the most sensitive and this curve has nearly a linear variation with moisture.

In summary of the non-resonant data, the measured parameters Z_{sc} and Z_{op} both show variation with the foliage moisture in magnitude and phase angle. However, the slope of the curves is not great, particularly above about 75% moisture content in the foliage. The best frequency to measure moisture appeared to be 50 MHz for this non-resonant OWL with the line spaced about 1.25 inches above the ground plane. The magnitude of the open circuit impedance appeared to be the best moisture indicator for the primary quanities while the loss tangent (δ) appeared to be the best secondary (calculated) indicator. The δ versus moisture curve would probably allow more accuracy in moisture determination than would the $|Z_{op}|$ curve.

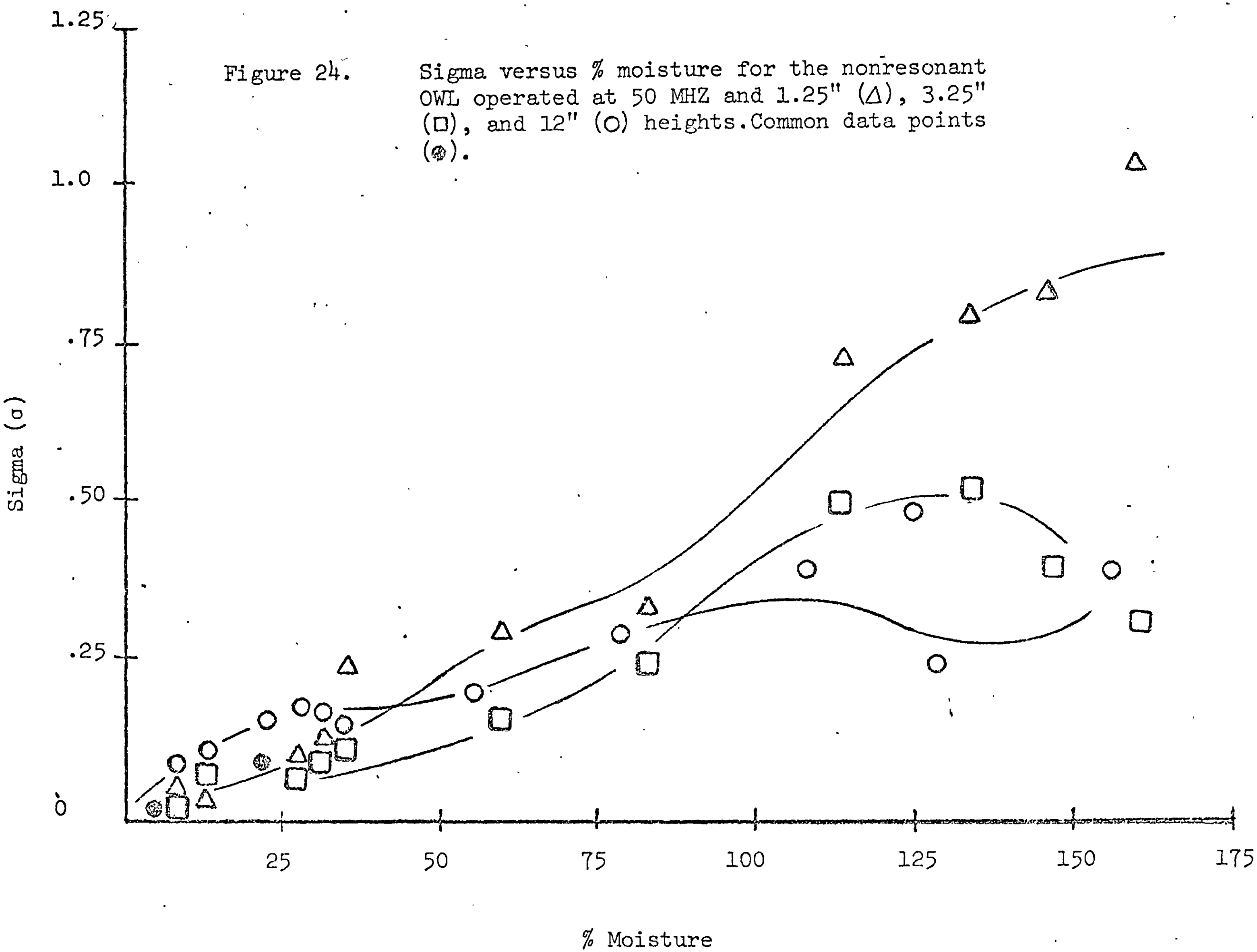


Figure 24. Sigma versus % moisture for the nonresonant OWL operated at 50 MHZ and 1.25" (△), 3.25" (□), and 12" (○) heights. Common data points (⊛).

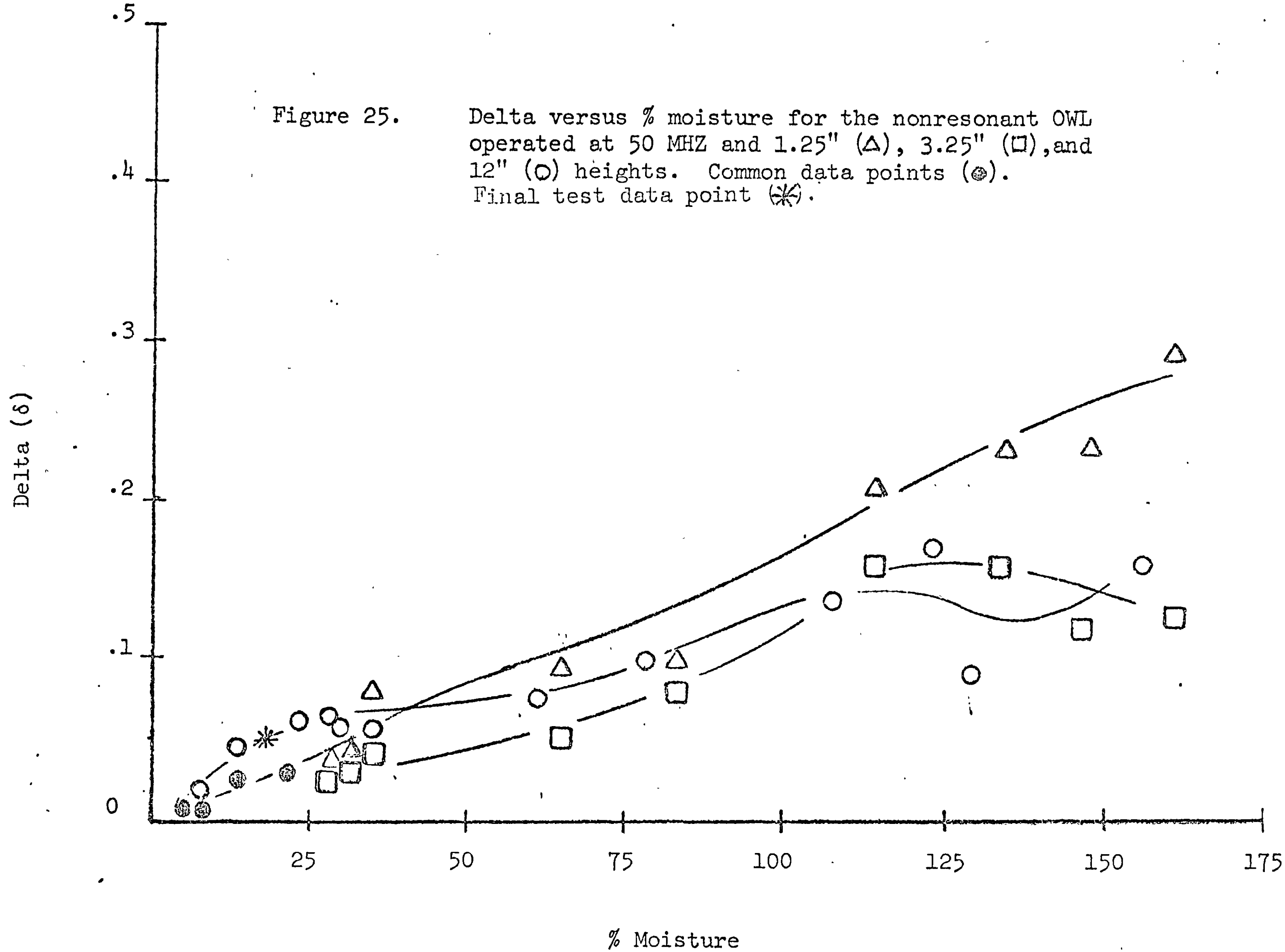


Figure 25. Delta versus % moisture for the nonresonant OWL operated at 50 MHZ and 1.25" (△), 3.25" (□), and 12" (○) heights. Common data points (◎). Final test data point (✳).

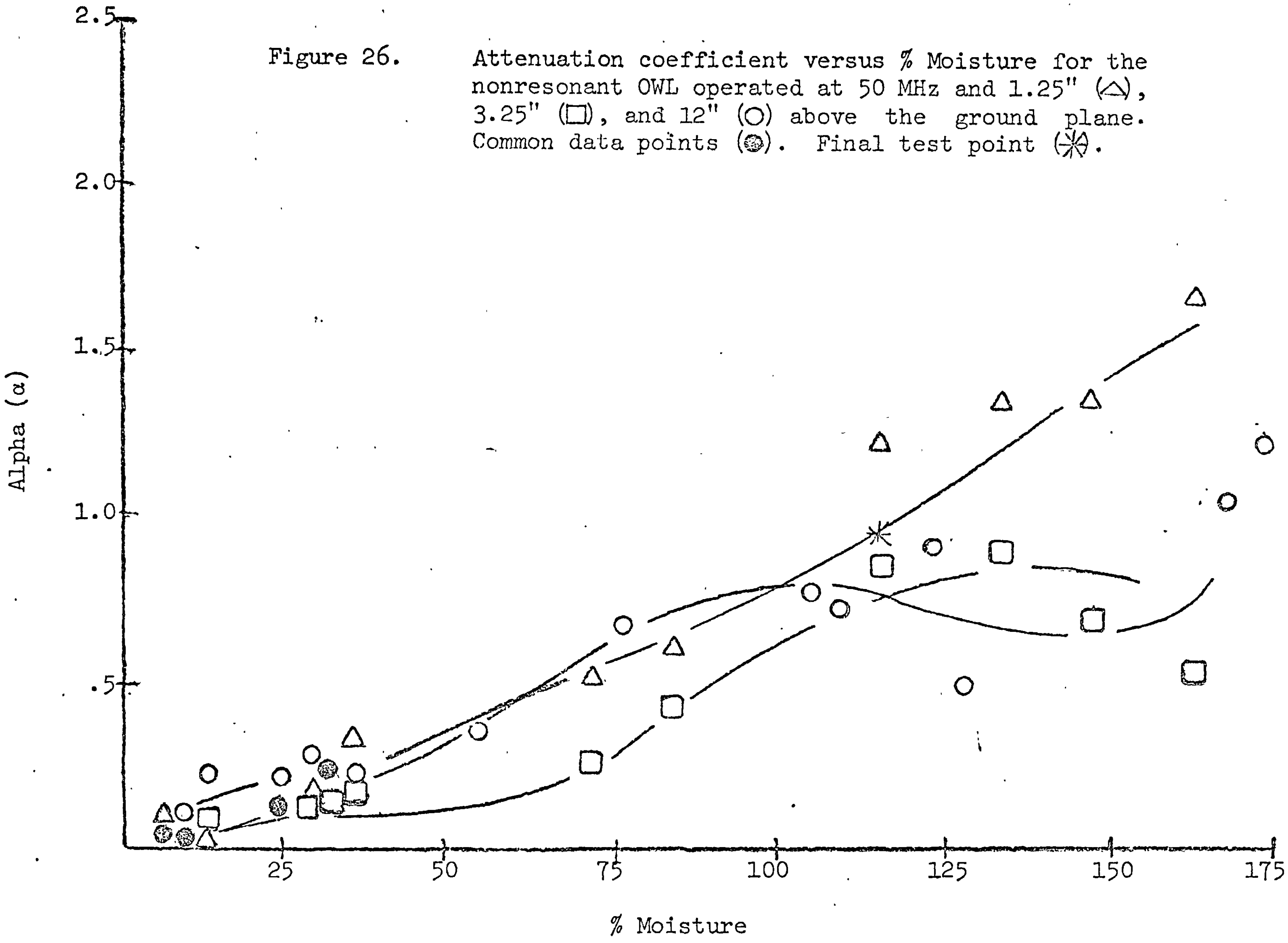


Figure 26. Attenuation coefficient versus % Moisture for the nonresonant OWL operated at 50 MHz and 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Common data points (●). Final test point (✳).

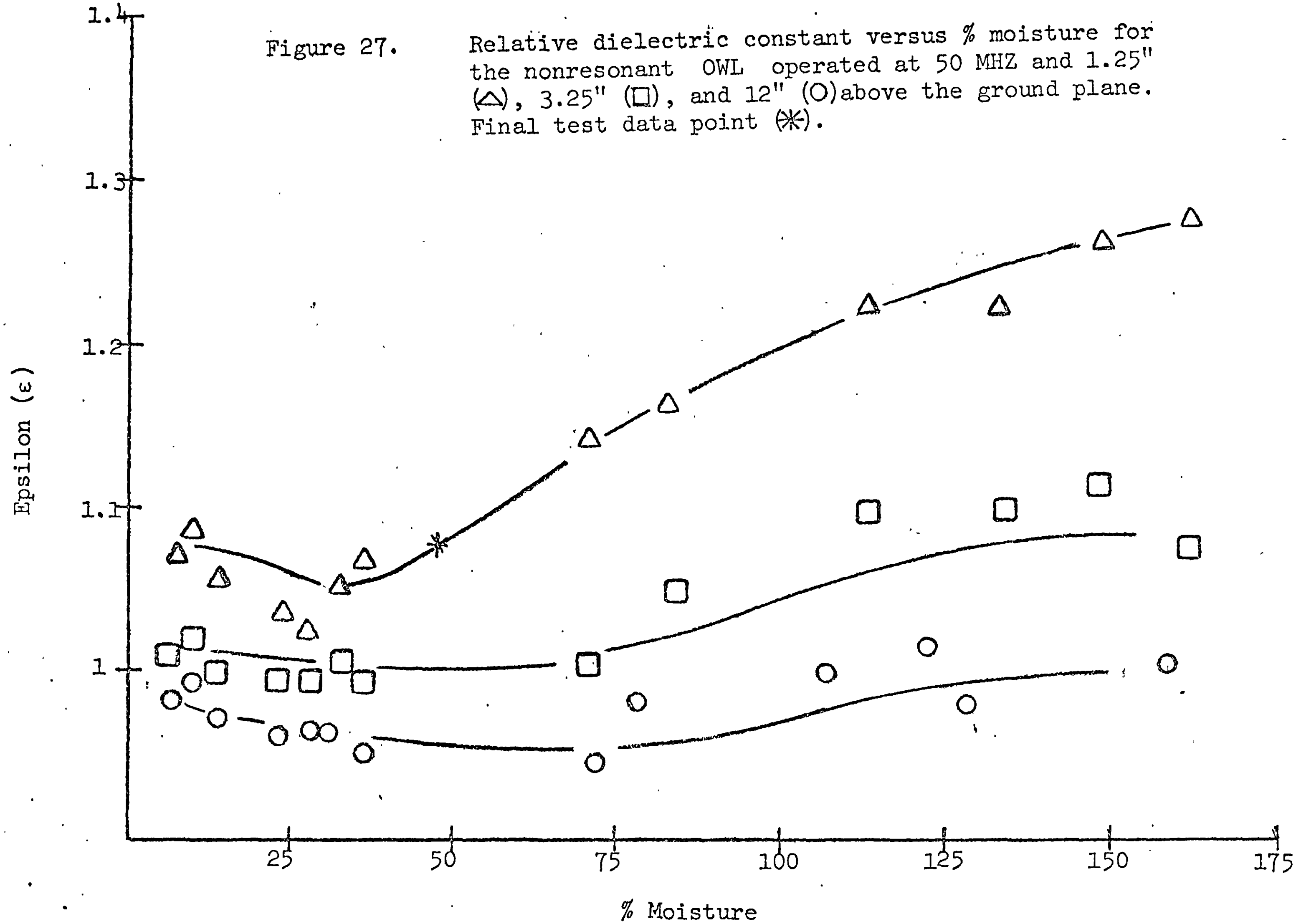


Figure 27. Relative dielectric constant versus % moisture for the nonresonant OWL operated at 50 MHZ and 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Final test data point (✳).

B. Resonant frequency data. As mentioned in section IV, the unbalanced OWL over the ground plane was also operated as a resonant line. The same data that was taken for the non-resonant line was taken for the resonant line but now an extra sensing parameter was available for observation as the moisture of the foliage changed--the resonant frequency of the line. The data for this section was taken by placing a short on the OWL and finding the frequency at which the input impedance (short circuit impedance) was entirely real $\mathrm{Im}(Z_{sc}) = 0$. This was done over a wide enough frequency range to observe four line resonances; one resonance at each multiple of a quarter wavelength from one to four ($\lambda/4$ to λ). It was expected that the short circuit impedance (magnitude) would be quite large at the frequencies where the OWL was a quarter or three quarters of a wavelength long and quite small at the frequencies where the OWL was one half or a full wavelength long. The reverse was expected for the magnitude of the open circuit impedance.

The magnitude of the short circuit impedance versus moisture is shown in Figs. 28 through 31. Each of the plots shows the measured curves at all three heights of the OWL. As expected the impedance was small at $\lambda/2$ and λ and quite large at $\lambda/4$ and $3\lambda/4$ (note the ordinate is a logarithmic scale in Figs. 28 and 30). The curves show that very good sensitivity to moisture change would be obtained with a shorted $\lambda/4$ or $3\lambda/4$ line particularly in the range of 0 to 75% moisture. Note also these curves of Figs. 28 to 31 show some indication that the line should be kept less than a full wavelength long and well below the twelve inch height. Figure 31 shows that at a full wavelength and twelve inches height the OWL was not behaving in a

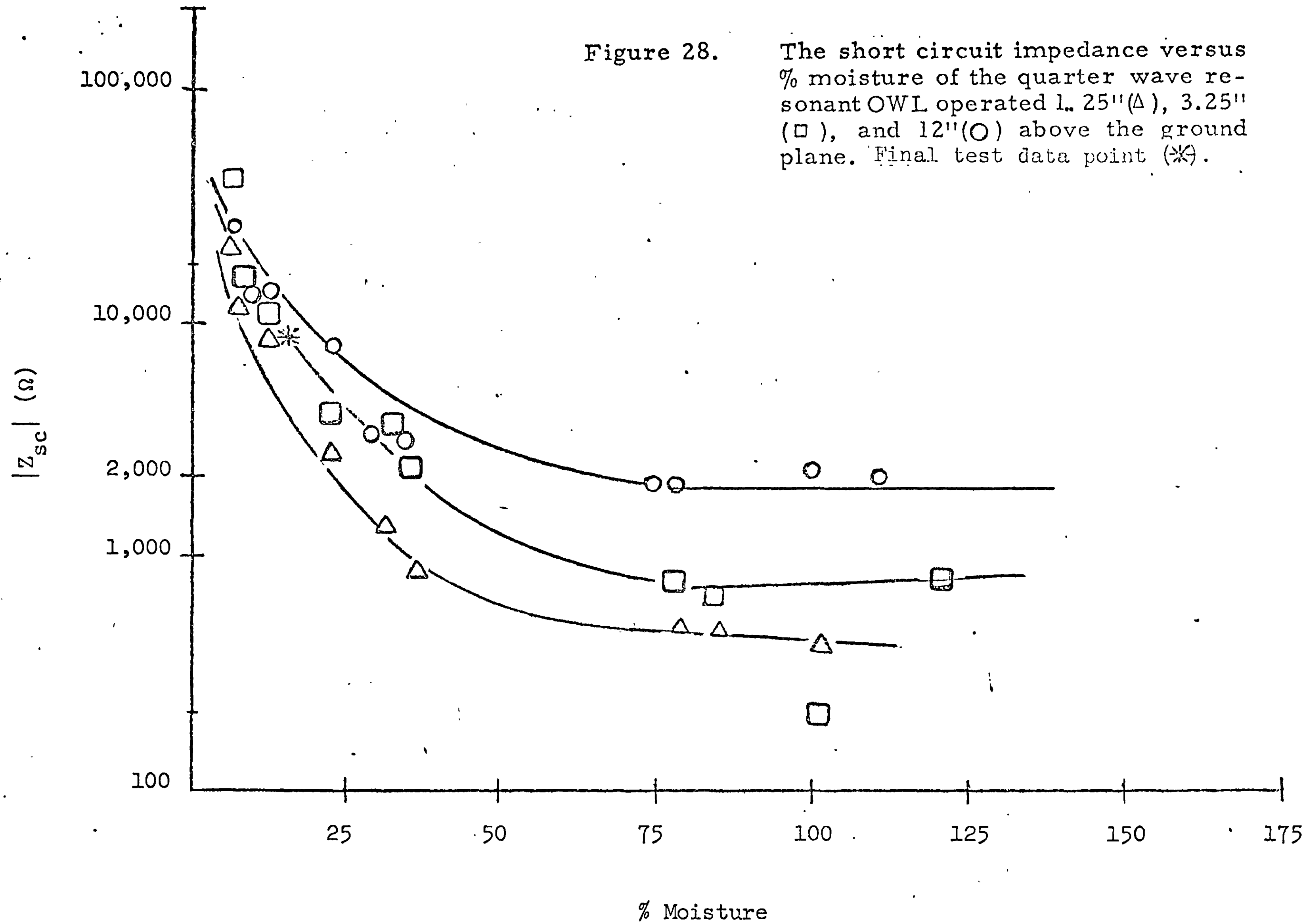


Figure 28. The short circuit impedance versus % moisture of the quarter wave resonant OWL operated 1.25"(Δ), 3.25" (□), and 12"(○) above the ground plane. Final test data point (✳).

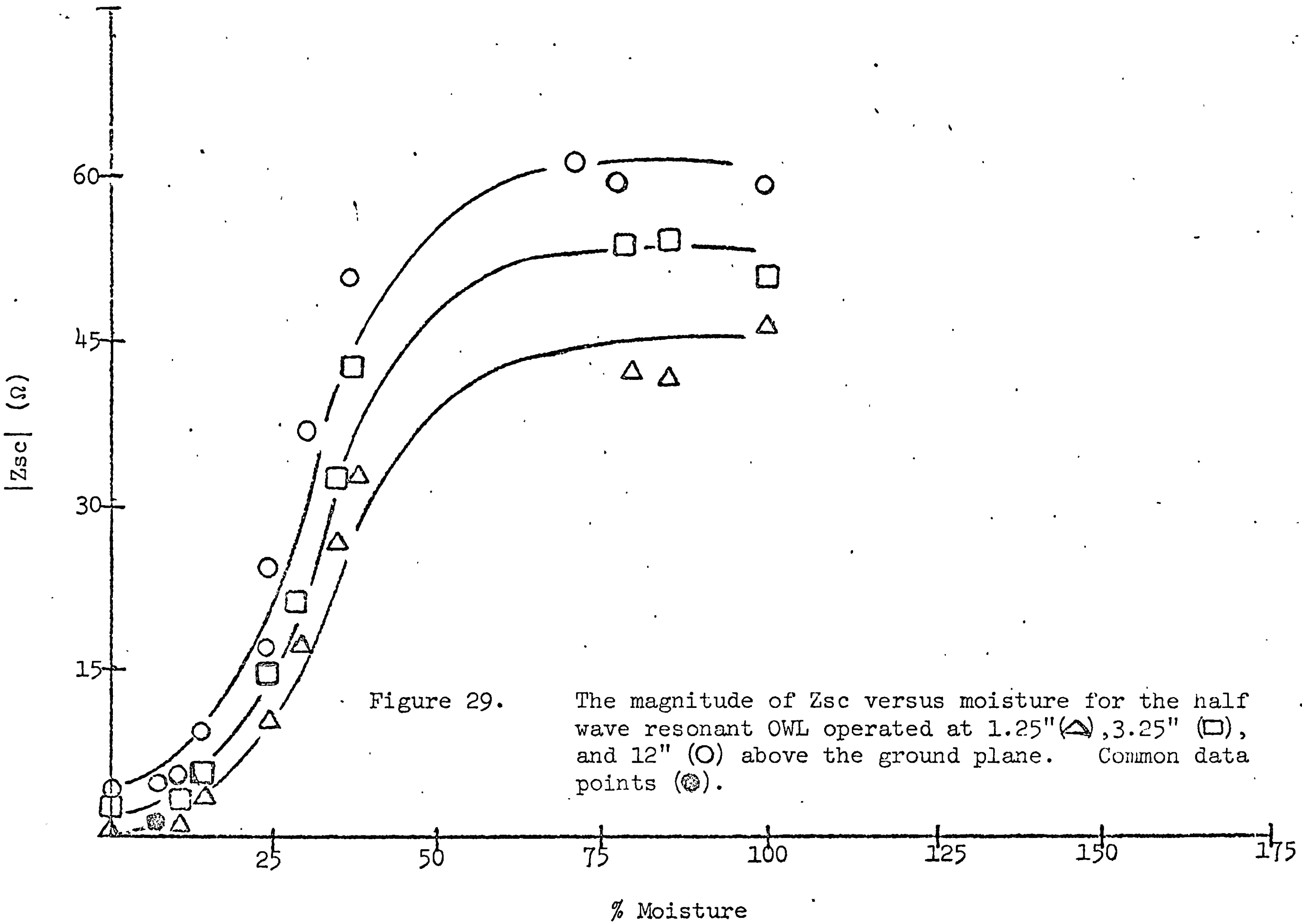


Figure 29. The magnitude of Zsc versus moisture for the half wave resonant OWL operated at 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Common data points (◎).

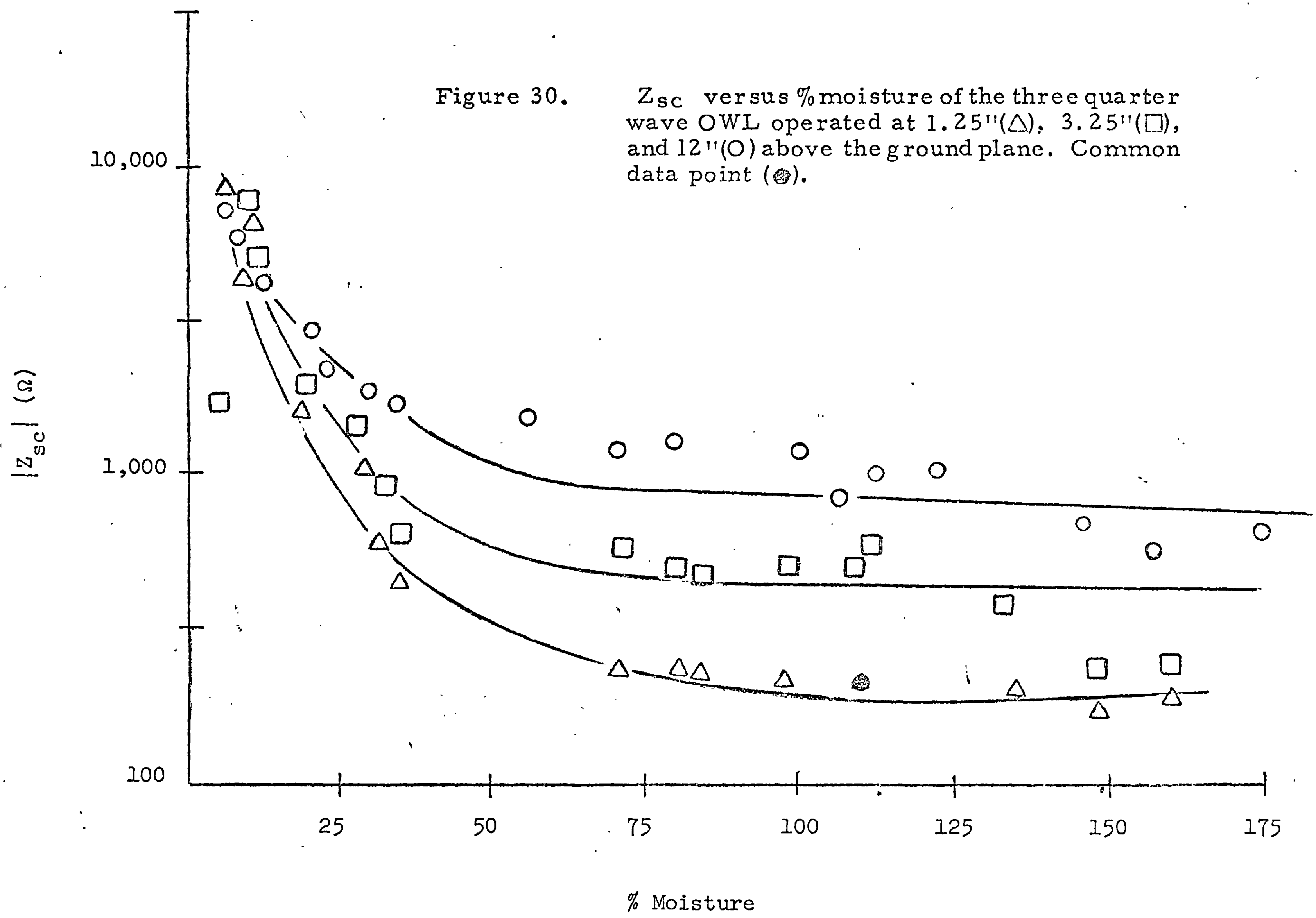


Figure 30. Z_{sc} versus % moisture of the three quarter wave OWL operated at 1.25"(△), 3.25"(□), and 12"(○) above the ground plane. Common data point (●).

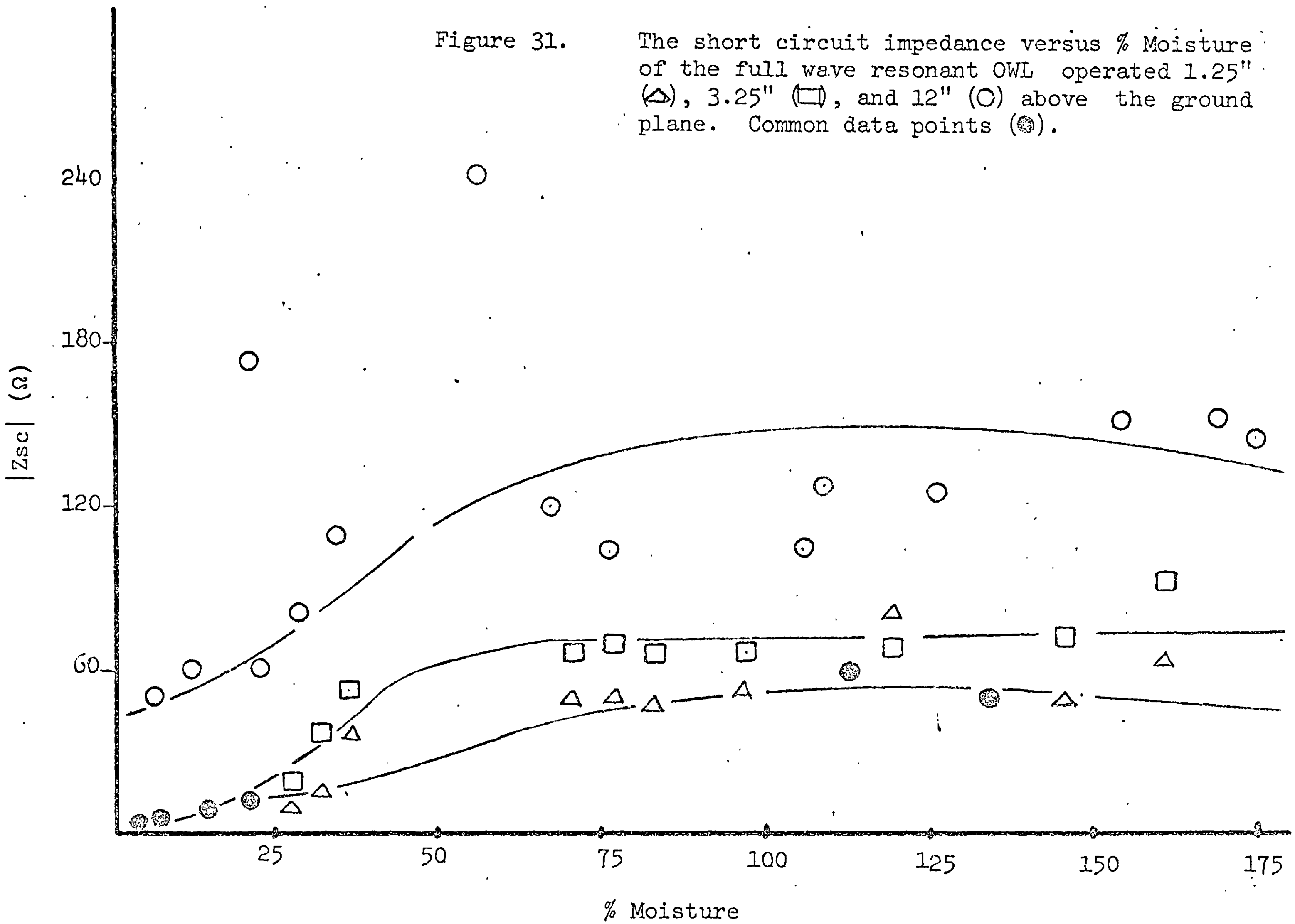


Figure 31. The short circuit impedance versus % Moisture of the full wave resonant OWL operated 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Common data points (◉).

predictable manner. An analysis is presented in Appendix B that shows that radiation from the line increases rapidly with frequency. That is, as the frequency is increased to make the line look like a full wavelength the "short" begins to behave like an antenna and to radiate energy. This decreases the line sensitivity to the surrounding foliage (less energy is available for sampling) but greatly increases the OWL sensitivity to surrounding objects that reflect the radiated energy. Hence the data points began to show bad scatter.

The magnitude of the open circuit impedance curves were quite similar to the short circuit data as can be seen in Fig. 32 which shows $|Z_{op}|$ versus moisture for the line a full wavelength long. Comparing Figs. 28, 30, and 32 a great similarity is seen. Note the data scatter is absent in $|Z_{op}|$ but begins to show up again in the open circuit data phase angle plots. These are shown in Figs. 32a and 32b. The phase data is well-behaved for a quarter wave line at all heights but for a half wave line the twelve inch height again shows scattered data points, indicating influences on the OWL beside the foliage moisture. Looking across all the resonant data presented so far it appears that the line length should be $\lambda/4$ or $3\lambda/4$ with a line height of between one and three inches.

The next data shown is the resonant frequency versus moisture data. All these data were taken with the line shorted since some of the previous data had indicated the open circuit load was not performing as a good open circuit. Figures 33 through 36 show the resonant frequency shift data.

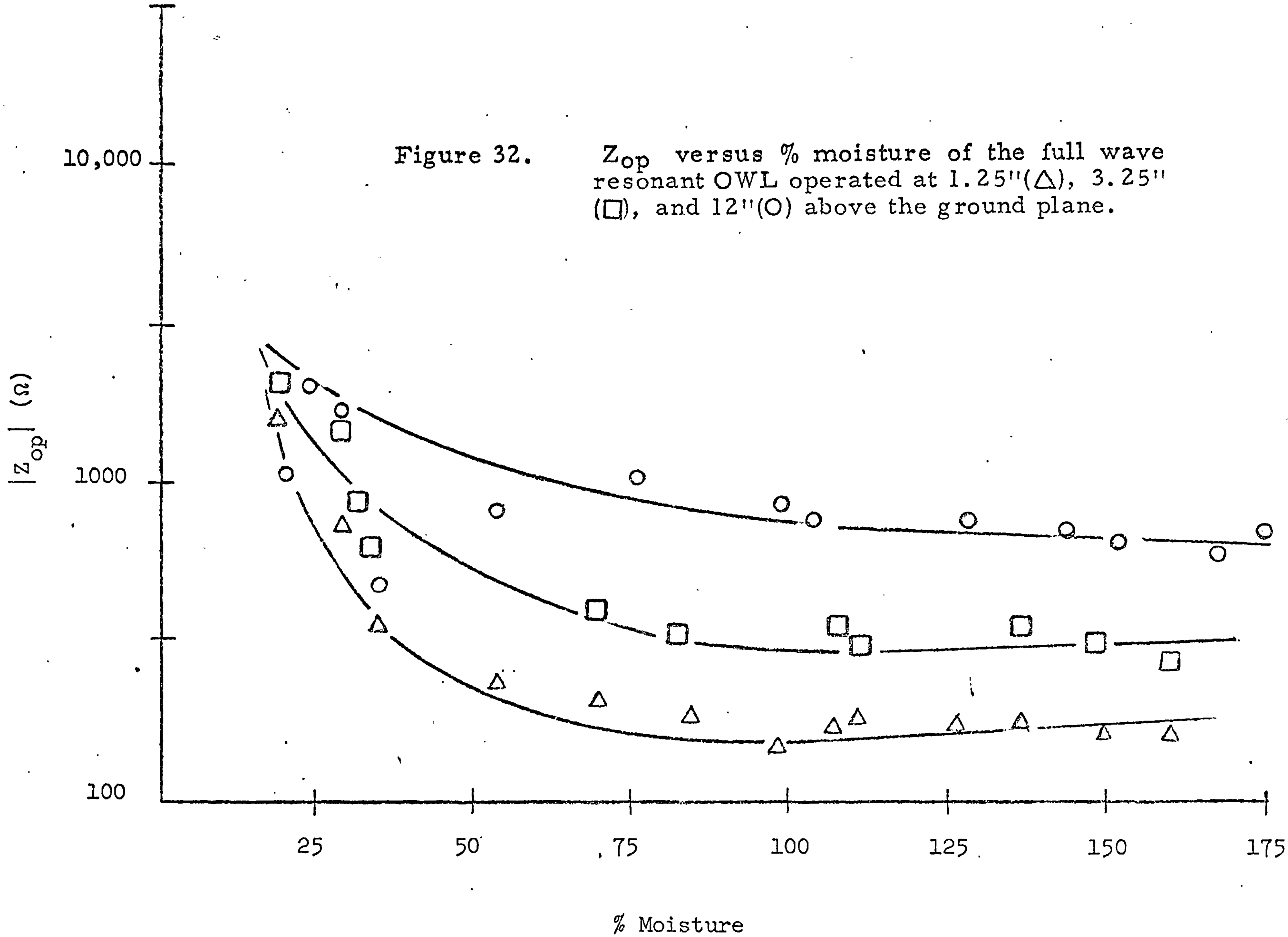


Figure 32. Z_{op} versus % moisture of the full wave resonant OWL operated at 1.25"(△), 3.25" (□), and 12"(O) above the ground plane.

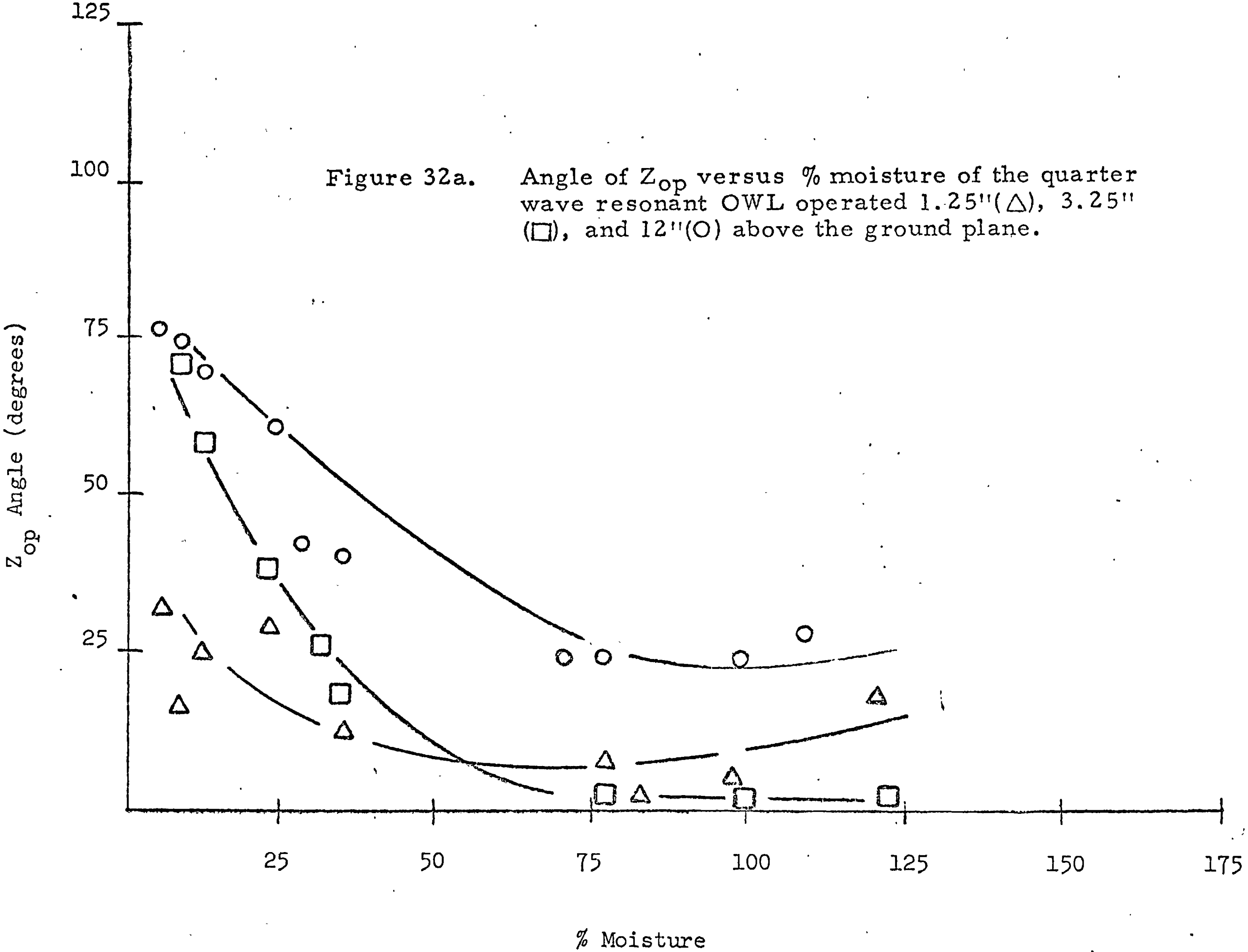


Figure 32a. Angle of Z_{op} versus % moisture of the quarter wave resonant OWL operated 1.25"(△), 3.25" (□), and 12"(O) above the ground plane.

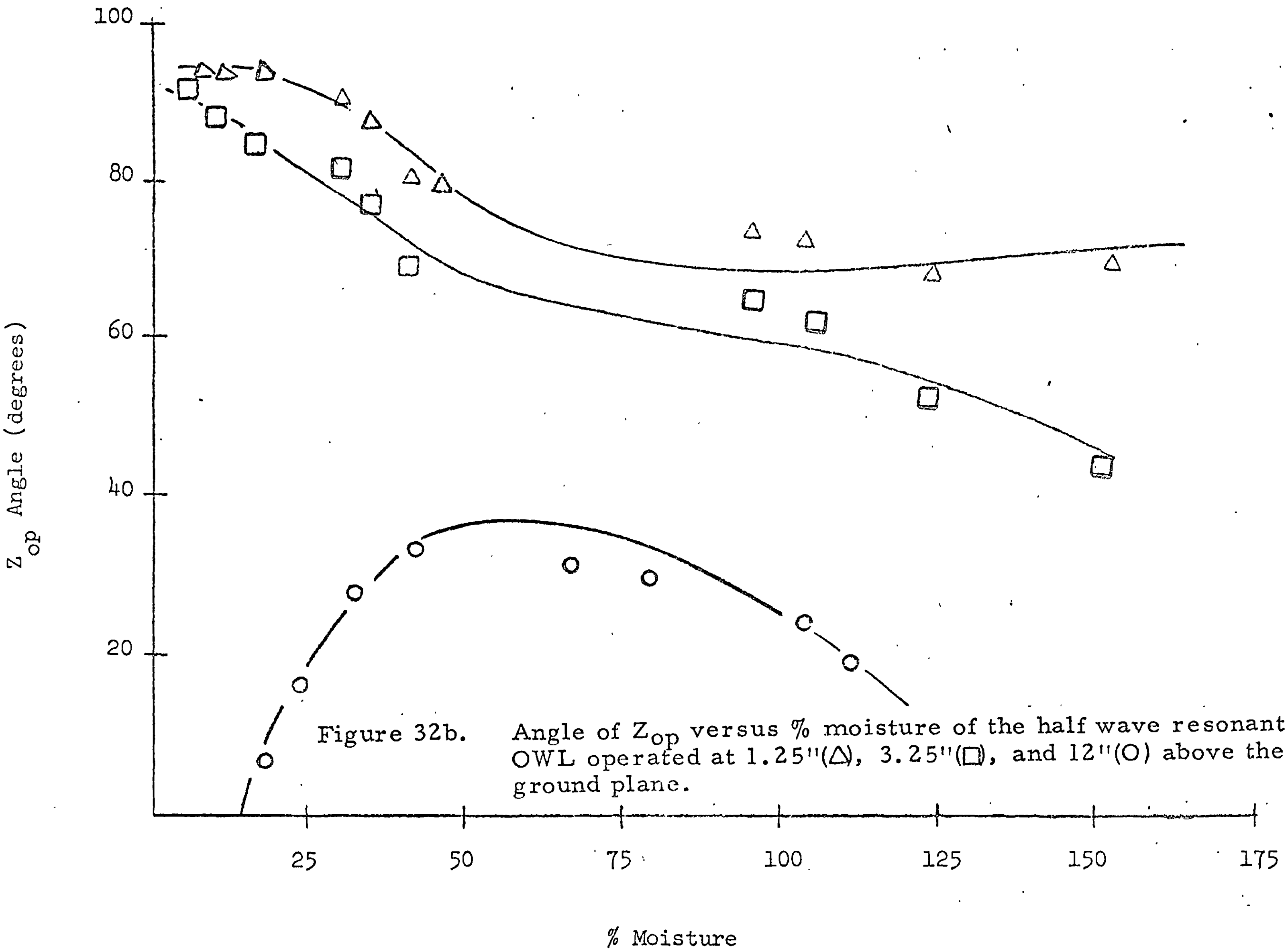


Figure 32b. Angle of Z_{op} versus % moisture of the half wave resonant OWL operated at 1.25"(△), 3.25"(□), and 12"(O) above the ground plane.

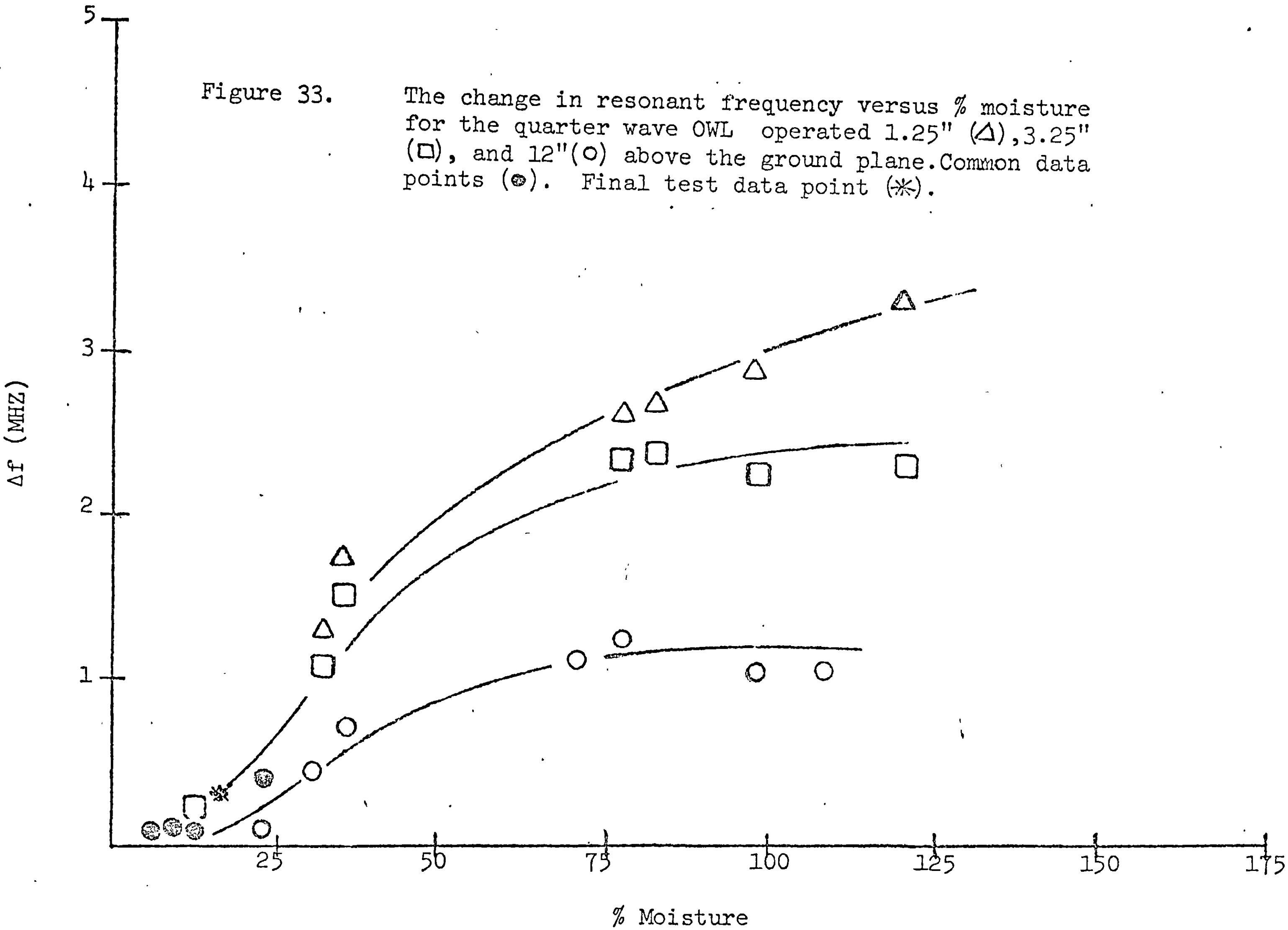


Figure 33. The change in resonant frequency versus % moisture for the quarter wave OWL operated 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Common data points (⊛). Final test data point (✳).

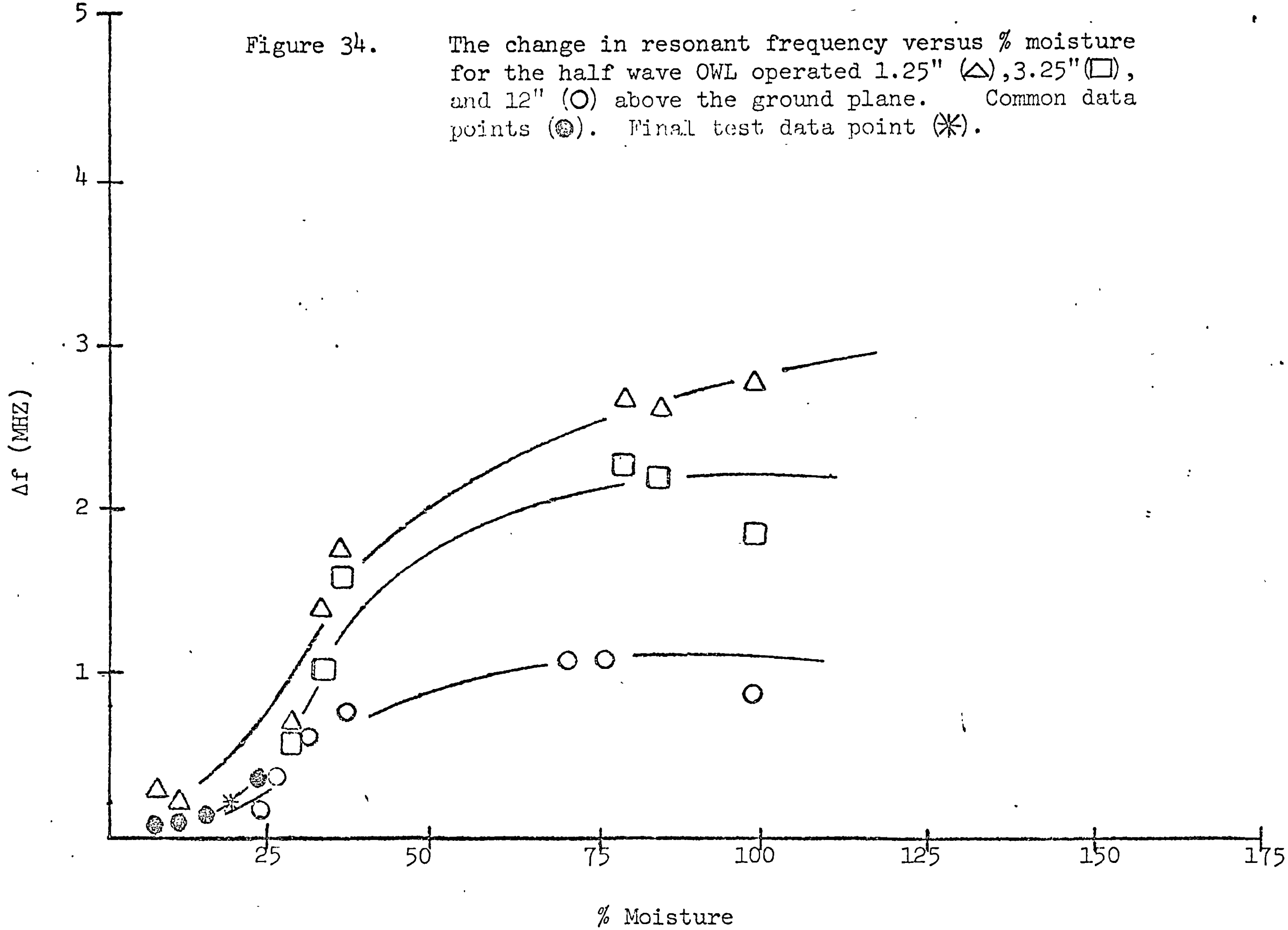


Figure 34. The change in resonant frequency versus % moisture for the half wave OWL operated 1.25" (△), 3.25" (□), and 12" (○) above the ground plane. Common data points (◍). Final test data point (✳).

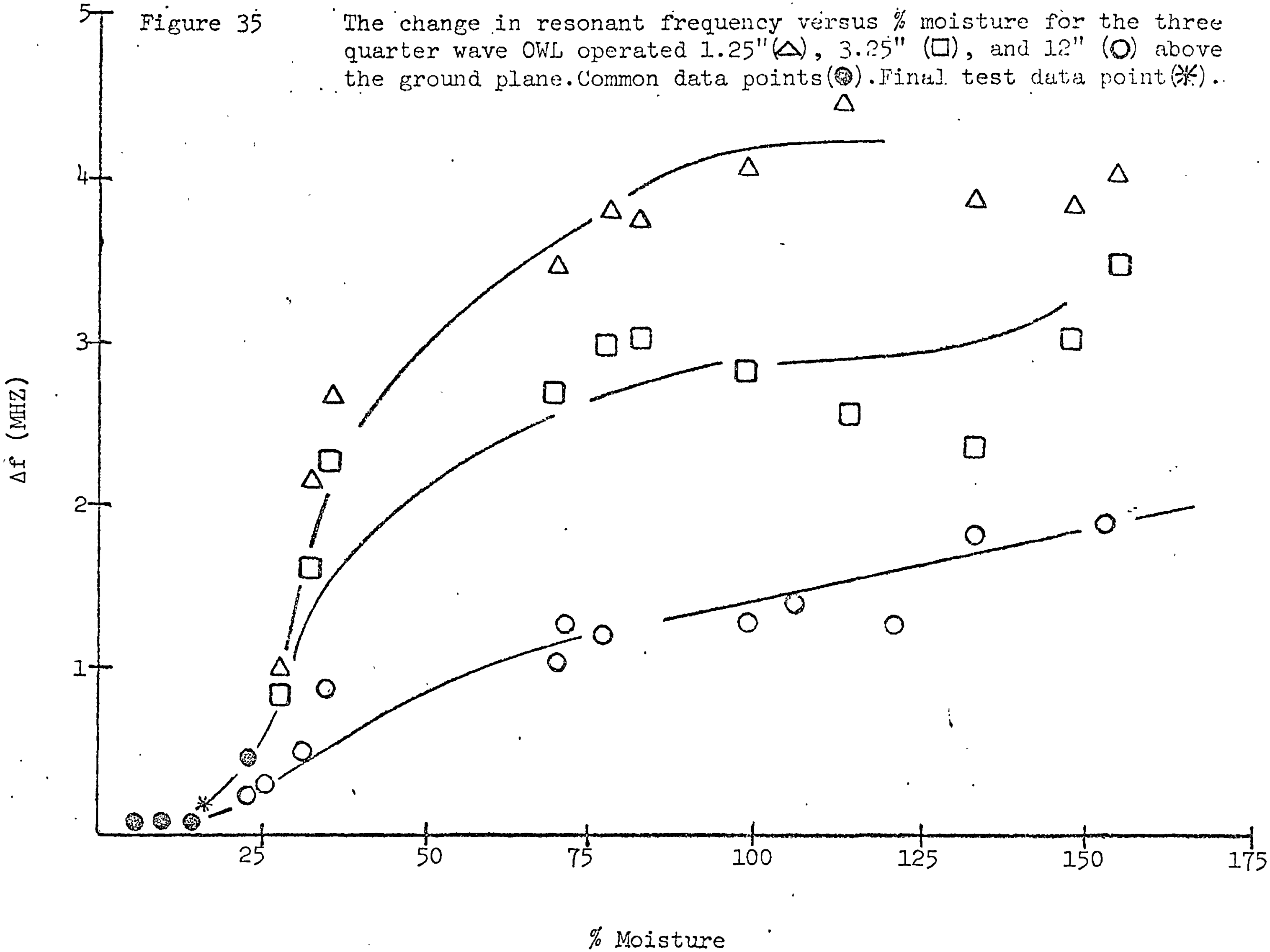


Figure 35 The change in resonant frequency versus % moisture for the three quarter wave OWL operated 1.25"(△), 3.25" (□), and 12" (○) above the ground plane. Common data points (◉). Final test data point (✳).

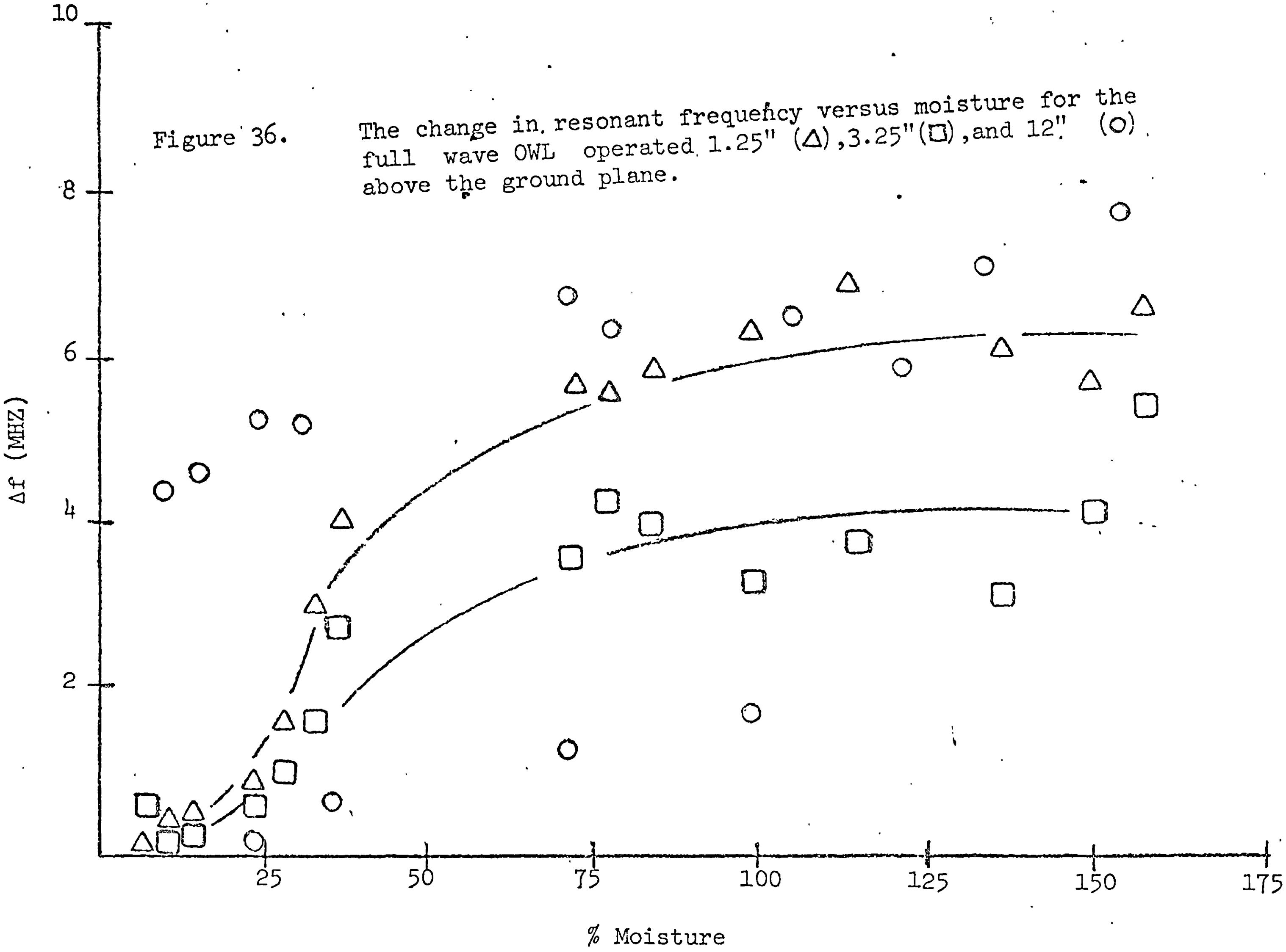


Figure 36. The change in resonant frequency versus moisture for the full wave OWL operated 1.25" (Δ), 3.25" (□), and 12" (○) above the ground plane.

The data indicates that the 1.25 inch line height with the OWL either $\lambda/4$ or 3 $\lambda/4$ long would give the most sensitivity and largest moisture range for a moisture sensing circuit. This data show promise as far as a remote moisture sensing terminal is concerned. The frequency shift over moisture contents from 0 to about 150% is several megacycles. The accurate determination of changes in frequency from some reference frequency is relatively easy to instrument for automatic operation. Shifts of several megacycles should be easy to detect with standard procedures that require only common components. Note once again that the data begin to show more scatter as the line approaches a full wavelength and as the height nears twelve inches.

Secondary parameters. Only two of the secondary parameters were calculated from the resonant frequency data, these being the relative dielectric constant (ε_r) and the loss tangent (δ). Experience with the non-resonant data had demonstrated these to be the most probable parameters for moisture sensing. Also the other two secondary parameters (α the attenuation constant and σ the conductivity) are directly related to ε_r and δ. The secondary parameters for the resonant data were calculated in a different way than they were for the non-resonant data. Some of the resonant data indicated a poor open circuit condition when an open termination was desired. This was particularly true at moisture contents above 100%. It is possible though somewhat tedious to develop expressions for (ε_r) and (δ) in terms of only the real and imaginary parts of the short circuit impedance. Using these expressions, a digital computer, and computer generated graphs one can arrive at values for (ε_r) and (δ).

Plots of the two secondary parameters for the resonant line at the three heights are shown in Figs. 37 through 40. One feature immediately obvious is that the full wavelength line should not be used as once again the data points for this line show bad scatter for both (ε_r) and (δ). The figures also indicate that the loss tangent δ shows the most promise as the moisture indicating parameter. An exception is noted Fig. 39, however. The 1.25 inch height data shows more scatter than either the 3.25 or 12 inch data. This could be due in part to the method used to calculate the secondary parameters.

A check on the resonant method of calculating the secondary parameters was done by using equation (19)

$$\varepsilon_r = (\frac{f_o}{f_r})^2 \qquad (19)$$

and defining the change in resonant frequency without and with foliage as $\Delta f = (f_o - f_r)$. Then one has

$$\varepsilon_r = \frac{\Delta f}{(f_r + 1)^2} \qquad (30)$$

as an expression to calculate ε_r for the resonant, shorted OWL. There was good agreement between theory and ε_r as calculated using only short circuit data.

In summary of the resonant frequency data, good variation of either $|Z_{op}|$ and $|Z_{sc}|$ was observed with moisture variation in the grain. The data also indicates a shorted OWL could be a good moisture sensing circuit if the line were kept less than a full wavelength long. The data suggest circuits a quarter or three quarter wavelength line as optimum. Once again the 1.25

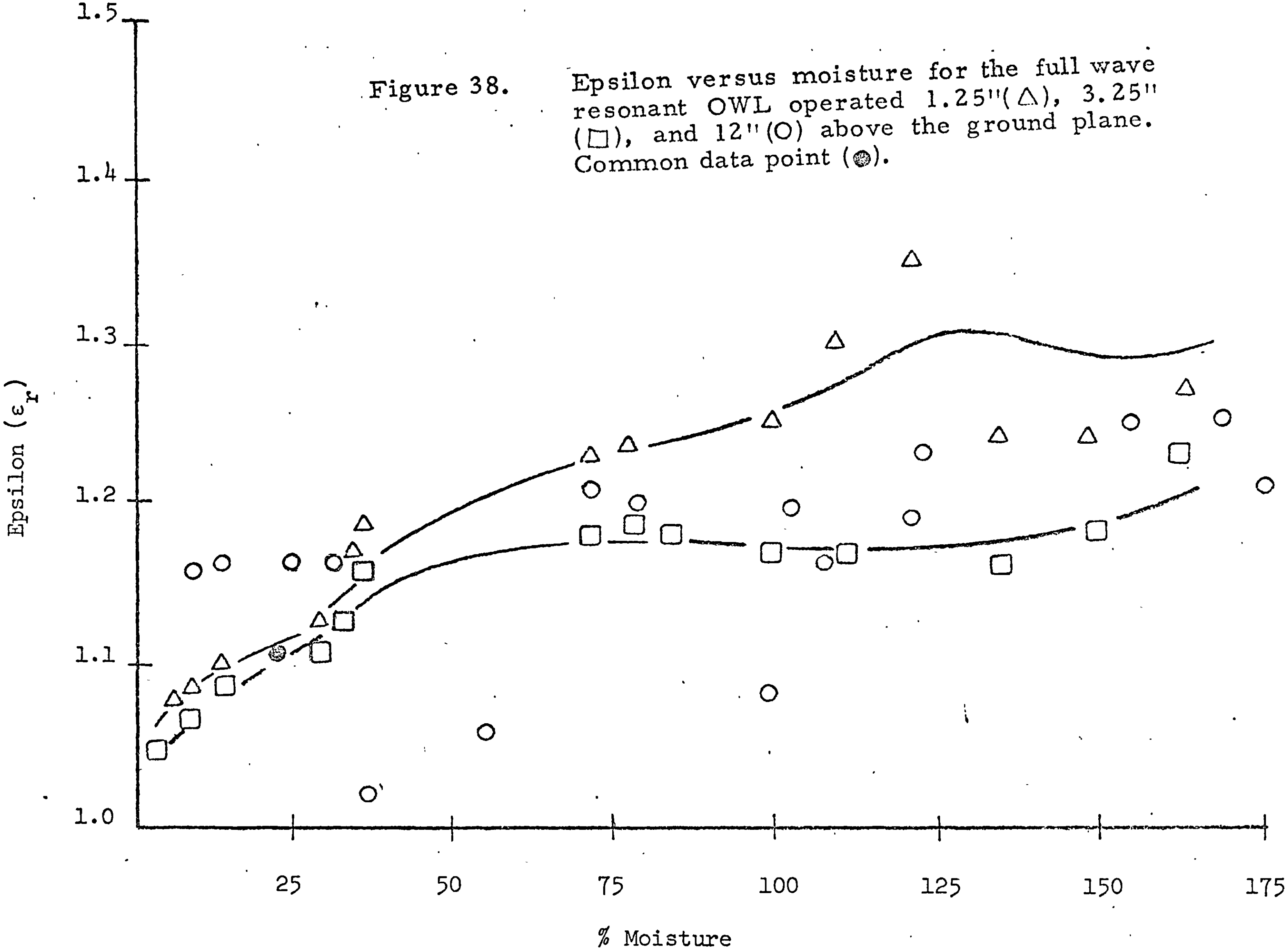


Figure 38. Epsilon versus moisture for the full wave resonant OWL operated 1.25"(△), 3.25" (□), and 12"(○) above the ground plane. Common data point (◉).

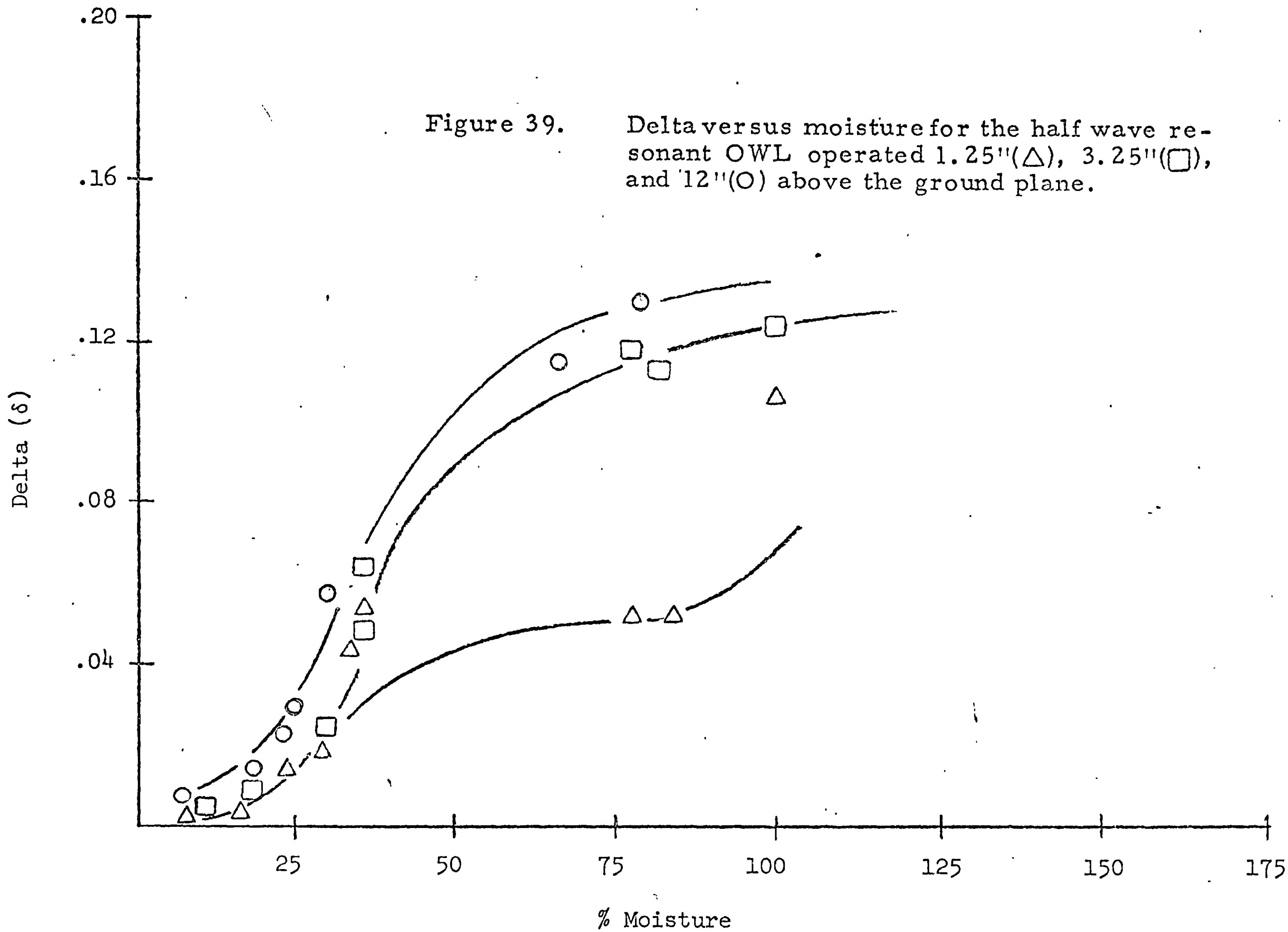


Figure 39. Delta versus moisture for the half wave resonant OWL operated 1.25"(△), 3.25"(□), and 12"(O) above the ground plane.

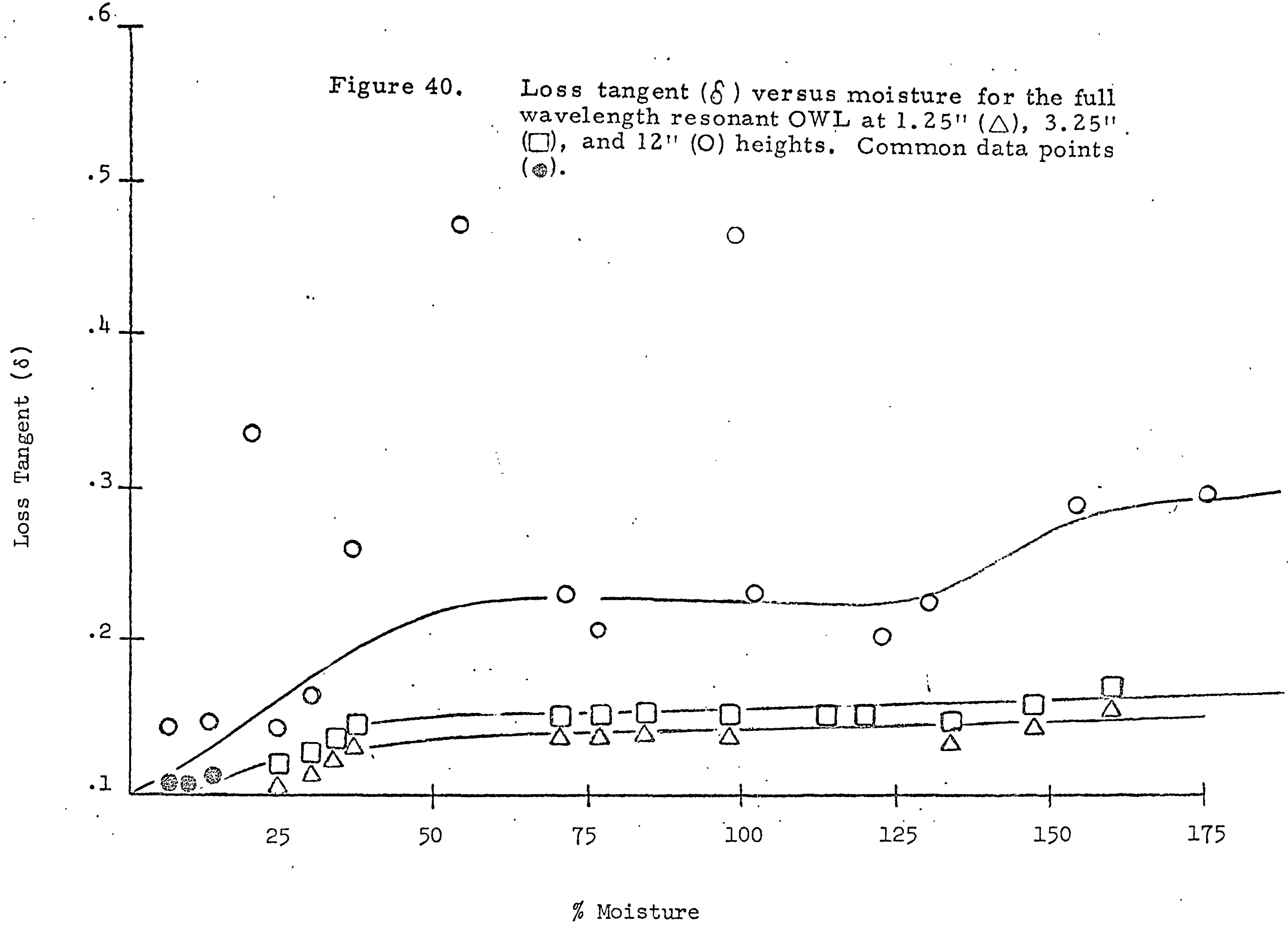


Figure 40. Loss tangent (δ) versus moisture for the full wavelength resonant OWL at 1.25" (△), 3.25" (□), and 12" (O) heights. Common data points (●).

inch line height appeared to be the best height. The resonant frequency secondary parameters show variation with foliage moisture with the loss tangent (δ) showing the most promise. The parameters are hard to obtain if good open circuit impedance data cannot be obtained and hence the resonant secondary parameters do not compare well convenience-wise to the primary parameters.

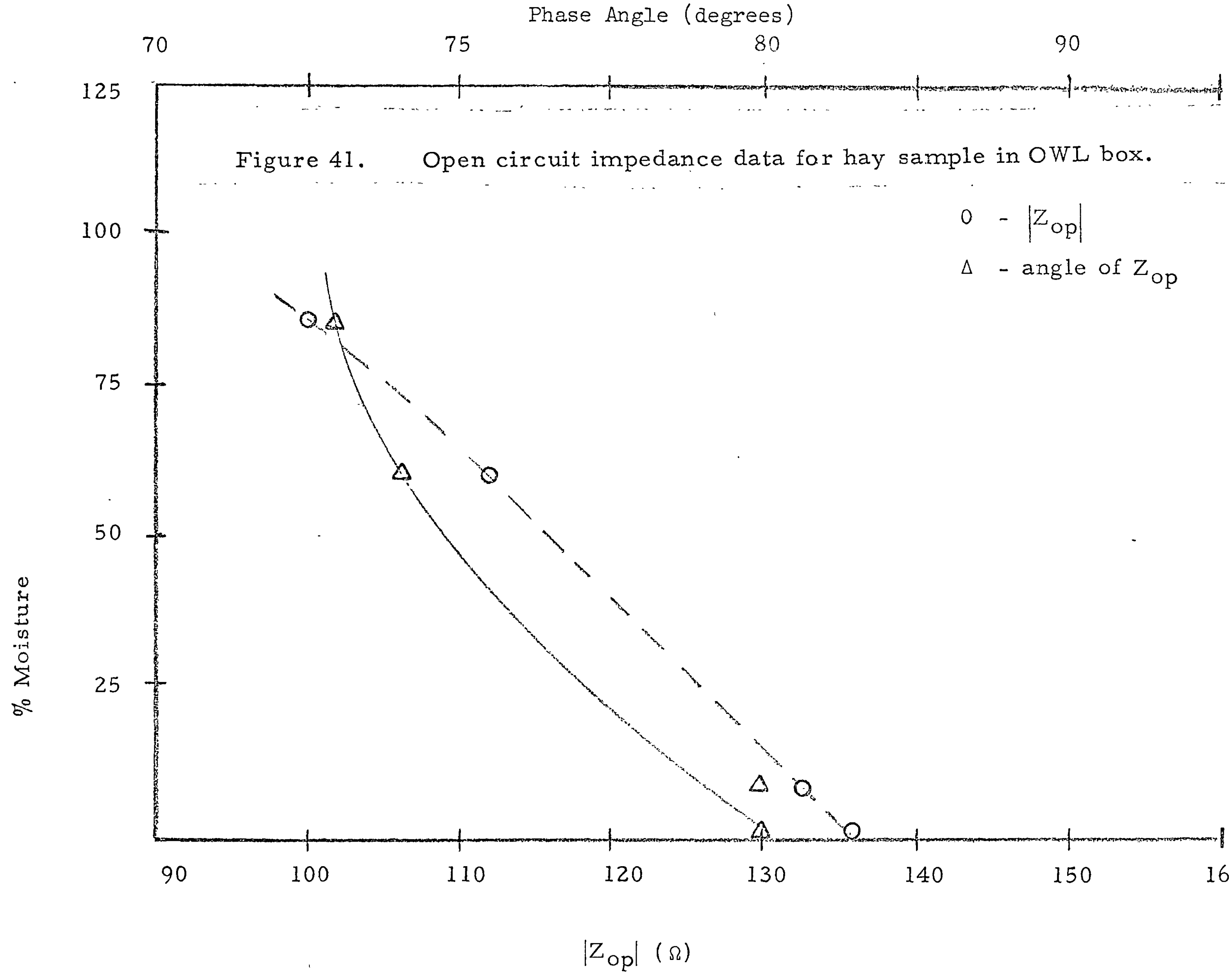
The OWL Box Structures

During the time the OWL was being operated in the growing grain, experiments were being run with open-wire lines surrounded by a test volume. A large amount of data was taken on these structures, with only representative samples of that data presented in the following paragraphs.

The first experiments were conducted with cut alfalfa hay as the test foliage. As previously discussed the test structure was a 25 inch cubic box with the OWL operated balanced at 58.2 MHz. The magnitude of the open circuit impedance and the open circuit phase angle versus the moisture in the hay is shown in Fig. 41, while the short circuit data is shown in Fig. 42. Primarily this data indicated that the lines would sense moisture change in the hay but too few data points were taken to establish repeatability or accuracy curves.

The next experiments involved whole sagebrush plants. The plants were cut and brought into the lab for testing in the box shown previously in Figs. 7 and 8. The magnitude of the open and short circuit impedances for the first set of sagebrush tested is shown in Fig. 43. The data indicates the OWL was operating at slightly less than half wavelength since

Figure 41. Open circuit impedance data for hay sample in OWL box.



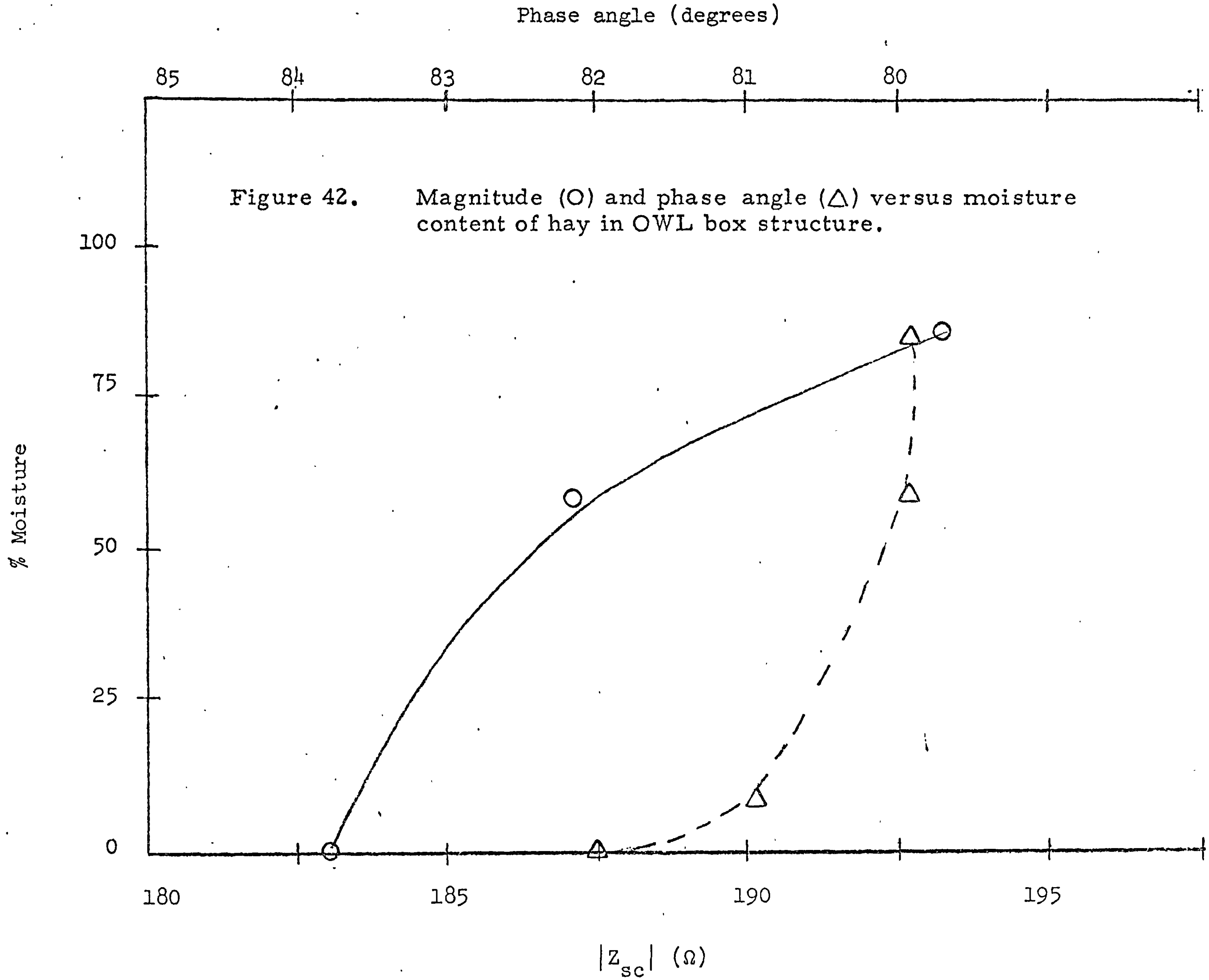


Figure 42. Magnitude (O) and phase angle (△) versus moisture content of hay in OWL box structure.

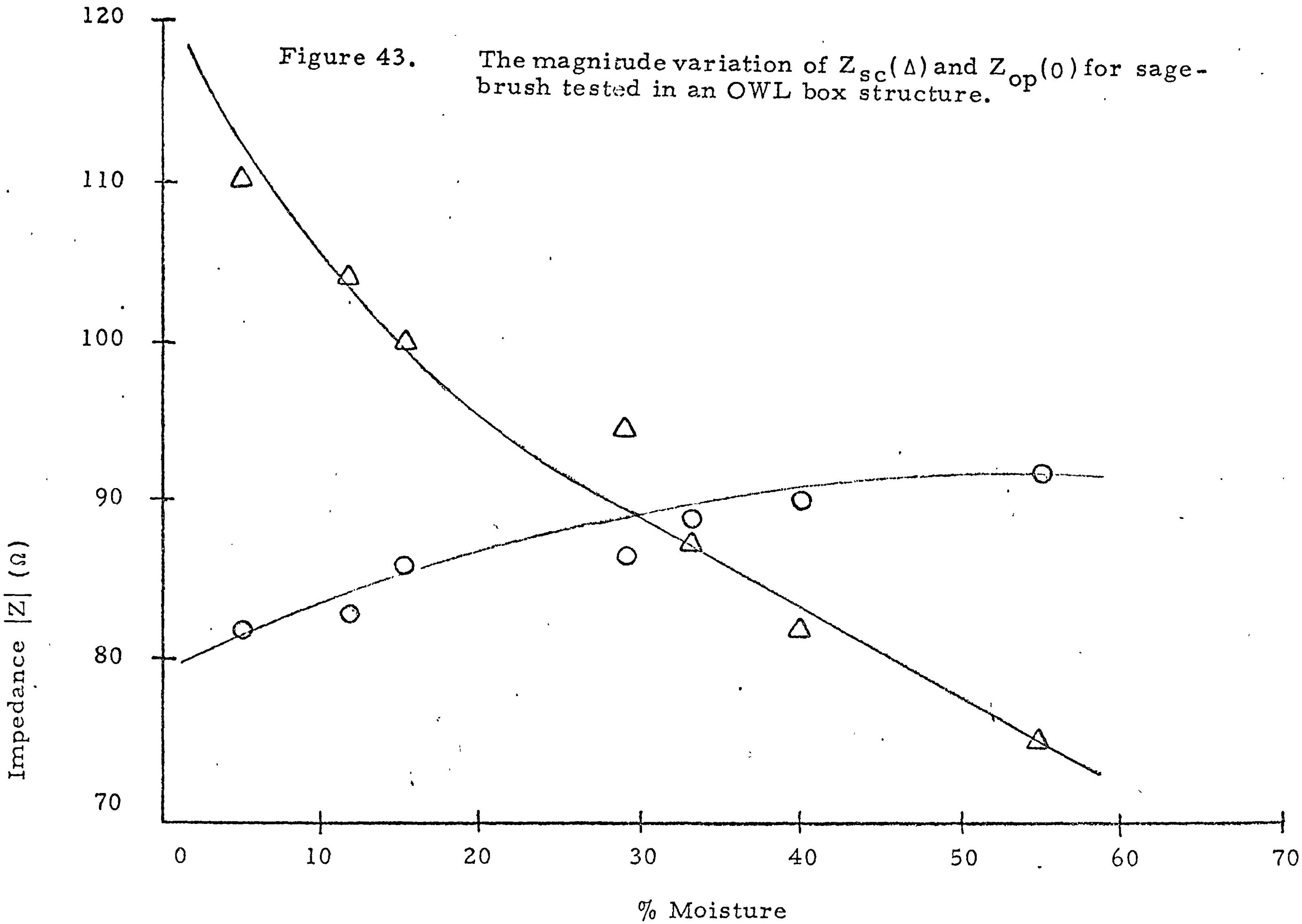


Figure 43. The magnitude variation of $Z_{sc}(\Delta)$ and $Z_{op}(0)$ for sagebrush tested in an OWL box structure.

the short circuit impedance decreased with moisture increase (wavelength decrease). This is consistent with the fact that the box was designed to be half wave long at 100 MHz (air dielectric) but was operated at 97.8 MHz since the balun tuned out at the latter frequency. A second set of sagebrush data is shown in Fig. 44. The brush used was a different sample and the transmission lines were each covered with a 5/8 inch i.d. glass tube to prevent the sage from shorting the line. The curves are virtually the same with slightly more linearity being exhibited by the glass covered lines. It is also seen that the glass covers on the line slightly decreased the OWL short circuit impedance sensitivity but increased the open circuit impedance sensitivity. This could have been caused by the dielectric constant of the glass covers on the lines moving the operating point of the box slightly further away from a half wavelength. The fact that Z_{op} did not change over as great a range as Z_{sc} as the moisture varied in the data of Fig. 43 may imply the OWL was not terminated in a "good" open circuit condition and there could have been some degree of line coupling. Hence the termination would have been somewhere between an open and a short circuit. The glass tubes would have partially corrected this since the fields in the data of Fig. 44 would have been more closely confined to the lines (hence less line coupling).

The data does indicate moisture sensing could be accomplished in this manner. Recall that the brush was not moved from the box during the entire test and that little shrinkage was observed. That is, it would be expected that bulk density caused errors would be at a minimum in this data. This test circuit might be made into a remote sensing terminal

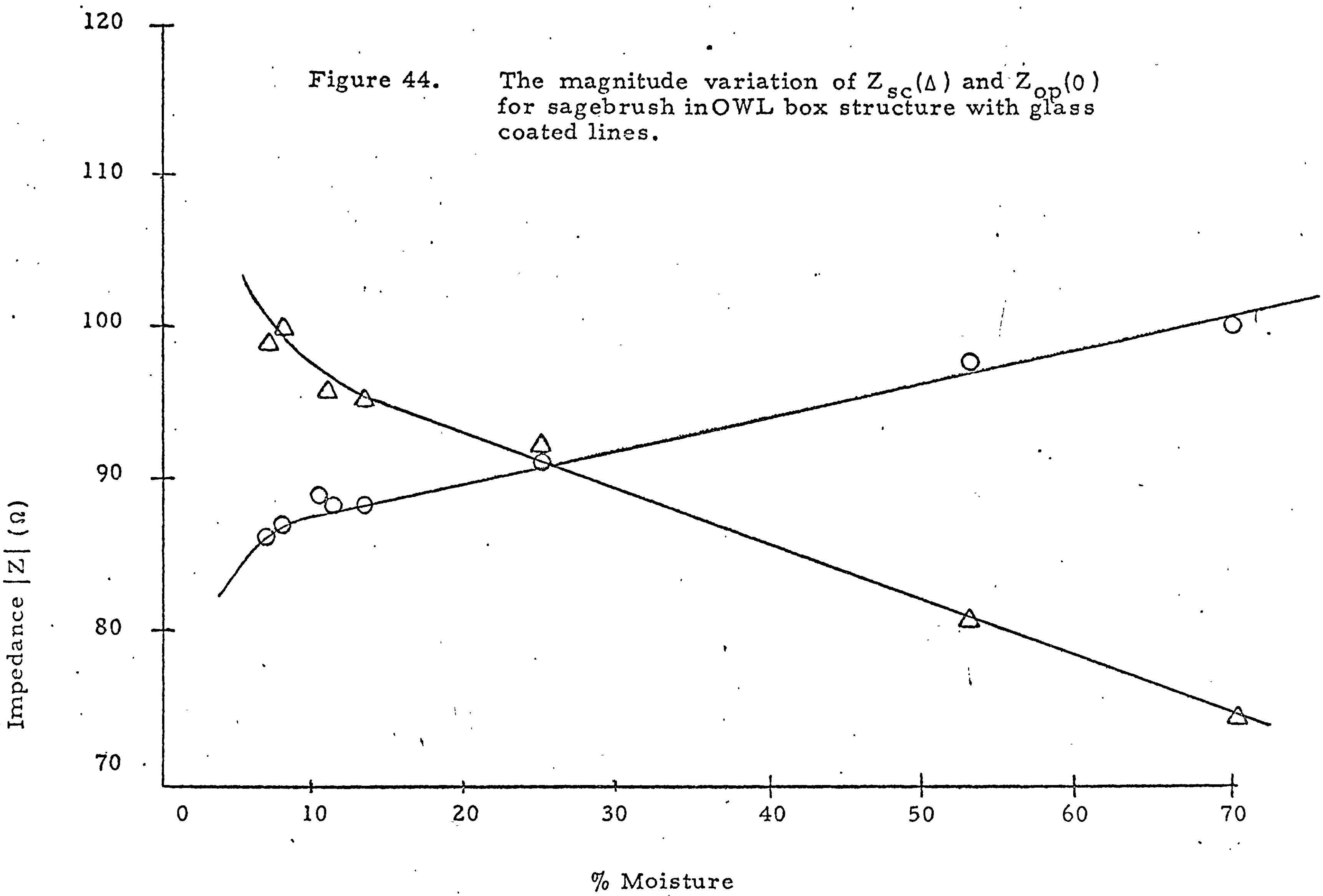


Figure 44. The magnitude variation of $Z_{sc}(\Delta)$ and $Z_{op}(0)$ for sagebrush inOWL box structure with glass coated lines.

since either open or short circuit impedance readings could be used to sense the moisture. The apparatus could be placed in living foliage. No operator would be required to change the line terminations but the initial set-up would require an operator.

Moisture and bulk density test with clipped lawn grass.

In the data presented up to this point very little information could be obtained as to bulk density effects on the testing circuits. This was one of the reasons the extensive studies using clipped lawn grass in OWL test boxes were undertaken. It would have been possible to conduct these tests in a manner similar to the sagebrush experiments except for two reasons. First, wet grass such as lawn grass or cheat grass, if it is chopped fairly fine (say 2 - 5 inch pieces), will pack considerably due to its own weight. If such green foliage is placed in a container and not turned frequently spoilage results in a day or two. Thus long before any valid moisture data could be obtained, (as the grass dried) chemical changes would have taken place in the foliage due to spoilage. The second reason the procedure had to be changed is that the grass volume changes considerably as it dries. Hence the experiments were run by placing samples in the various test volumes and recording the impedance change with respect to air data (air only in the test volume).

The data for the wooden box shown previously in Fig. 9 and that for the plastic box of Fig. 10 is shown in Figs. 45 through 47. The shape of the curve sketched through the data is similar for each of the three circuits. One major difference is that the plastic box with either the symmetric or

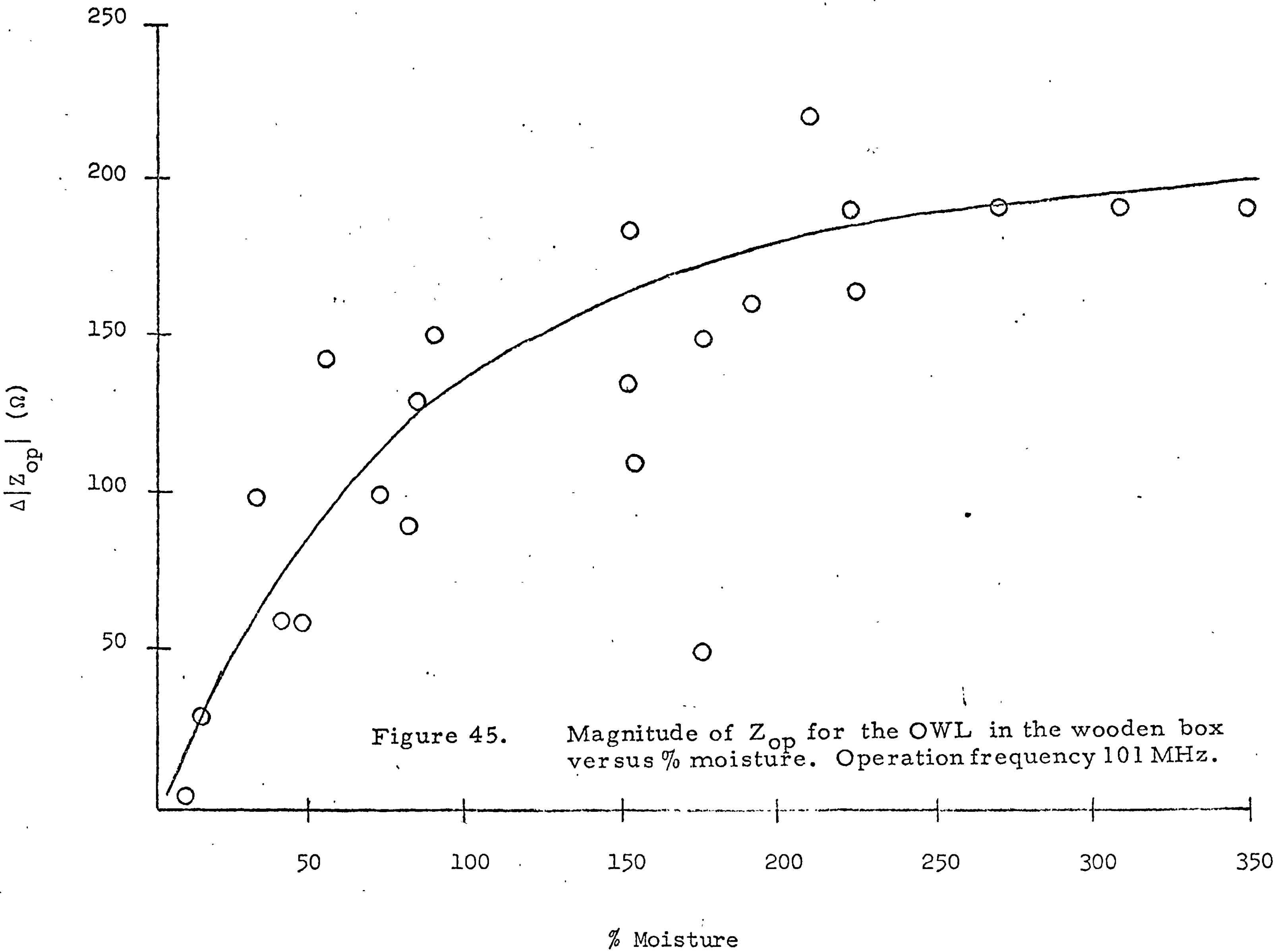


Figure 45. Magnitude of Z_{op} for the OWL in the wooden box versus % moisture. Operation frequency 101 MHz.

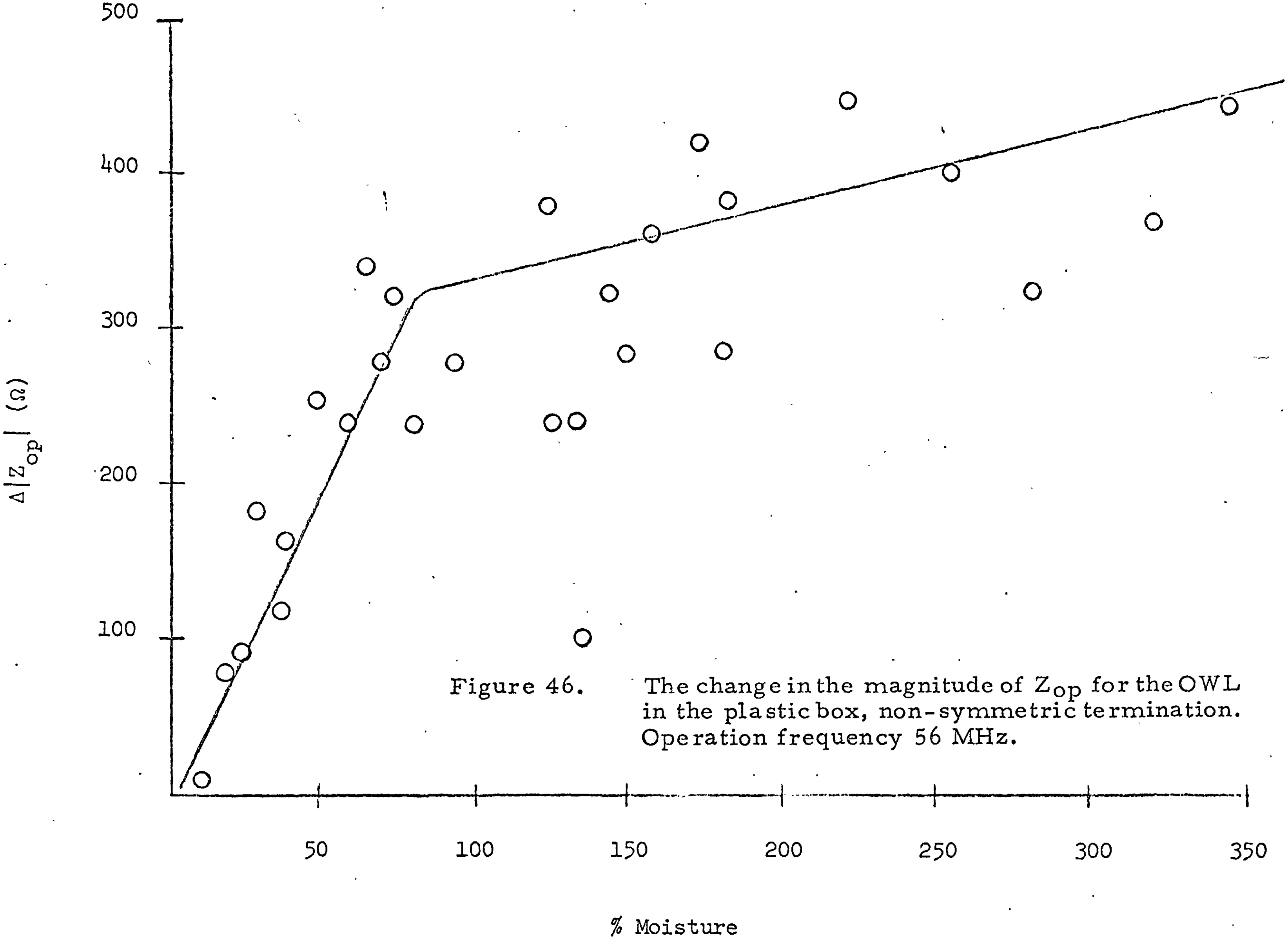


Figure 46. The change in the magnitude of Z_{op} for the OWL in the plastic box, non-symmetric termination. Operation frequency 56 MHz.

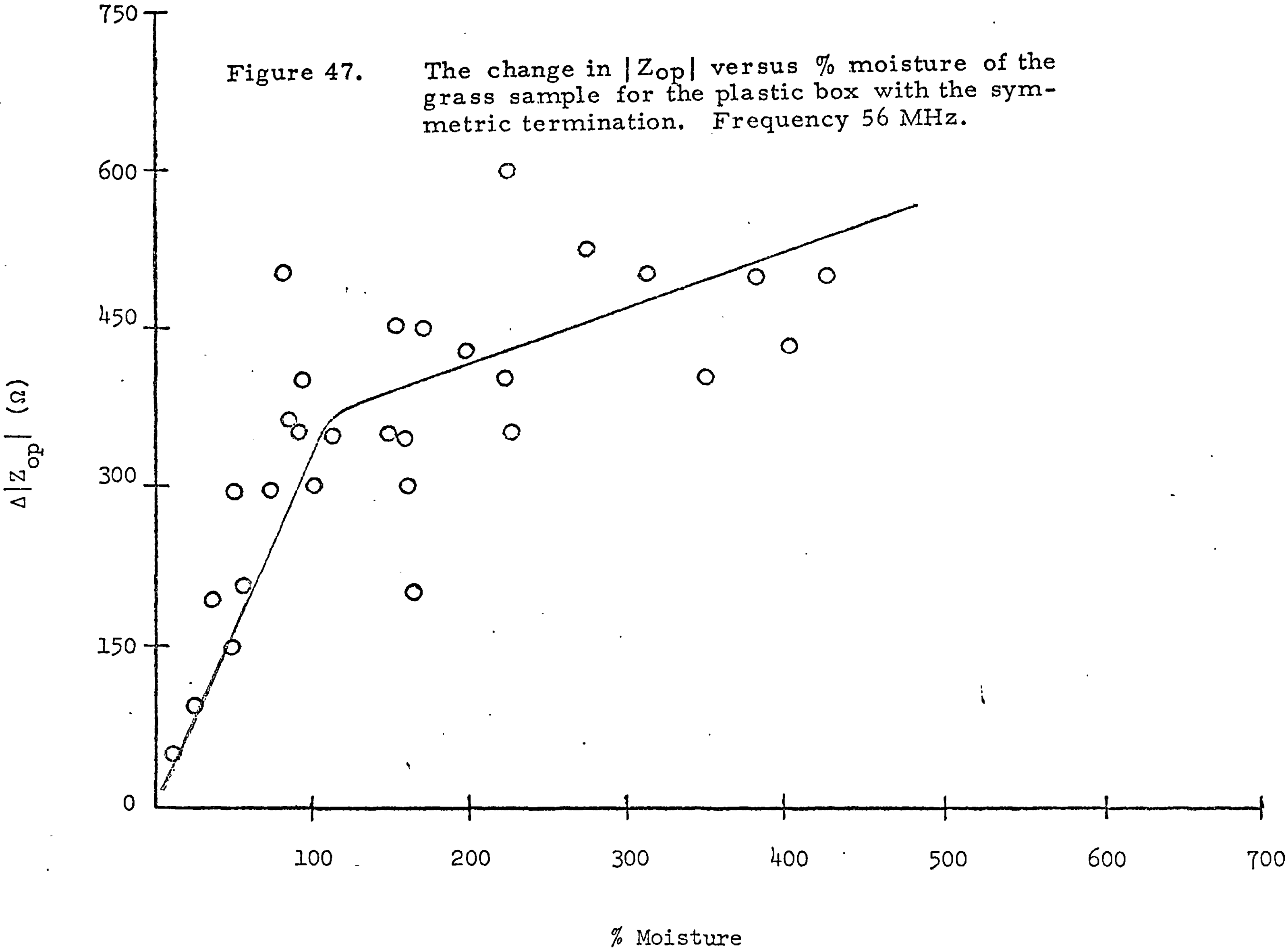


Figure 47. The change in $|Z_{op}|$ versus % moisture of the grass sample for the plastic box with the symmetric termination. Frequency 56 MHz.

non-symmetric termination (see Fig. 11a, b) had roughly three times the change of sensing parameter as compared to the wooden box. It should be pointed out that all the data shown was taken with the load terminals of the OWL open circuited. Another prominent feature of the Δ Z versus % moisture curves is the rather abrupt change in the curves at 100% moisture. This feature is quite prominent in Figs. 46 and 47 for the plastic box. As mentioned previously it appears from the data that some other effect may be coming into play at foliage moisture above 100%. A third, very obvious feature of the curves in Fig. 45, 46, and 47 is the points indicate the trend of the data but obviously could not be considered calibration curves.

The data was taken several ways. First constant weights of grass were used but this data showed bad scatter as soon as fairly wet grass was tested (above 100%). The wet grass did not fill the test volume if a sample weight was used corresponding to a full test volume weight of dry grass. If enough wet grass was used to fill the test volume, that same weight of dry grass could not be packed into the test volume. Tests were then run by filling the test volume each time, taking the reading and then weighing the sample. Fairly consistant results were obtained until 100% moisture was reached. Above this point the data scattered again since there was no way to define a "full" test volume. Grass with greater than 100% moisture would vary 300 to 500 grams in sample weight using a "full" test volume simply because of slight packing or the lack of packing during filling of the

volume. This again scattered the data points. Another method tried was filling the test volume with grass until no further change would be observed in the sensing parameter. Again the scatter of data points was bad except below about 100%. Even in the range of 50 to 100% the scatter was not small enough to make this method reliable.

It was decided to check all the data points to see if the change in sensing parameter was due to the actual water content of the grass or if most of the change in sensing parameter were due to volume and bulk density variation. For each data point the water present in the grass sample was calculated and these points plotted versus the sensing parameter $\Delta Z'$. The results are shown in Figs. 48 through 50. It is immediately seen that indeed the water in the grass is certainly causing a great deal of the change in the sensing parameters and that the scatter of the data points has been considerably reduced in Figs. 48 through 50. Note that the greatest reduction in data scatter occurred for moistures above 100%. Many of the data points in this region were taken by filling the test volume until no further change occurred in the sensing parameter. As a result a wide range of sample weights occurred. Consider two such points. For one sample 955g at 350% moisture a reading ΔZ of 190 recorded. Another sample of 1020g. at 226% moisture had the same ΔZ reading. Calculating the water weight in the test volume shows 740g for the first sample and 710 g for the second sample. Thus a plot of ΔZ versus % moisture would show data scatter for these two samples but ΔZ versus water in the box would show little scatter. Thus by plotting the sensing parameter versus the actual water in the sample the data scatter caused by bulk den-

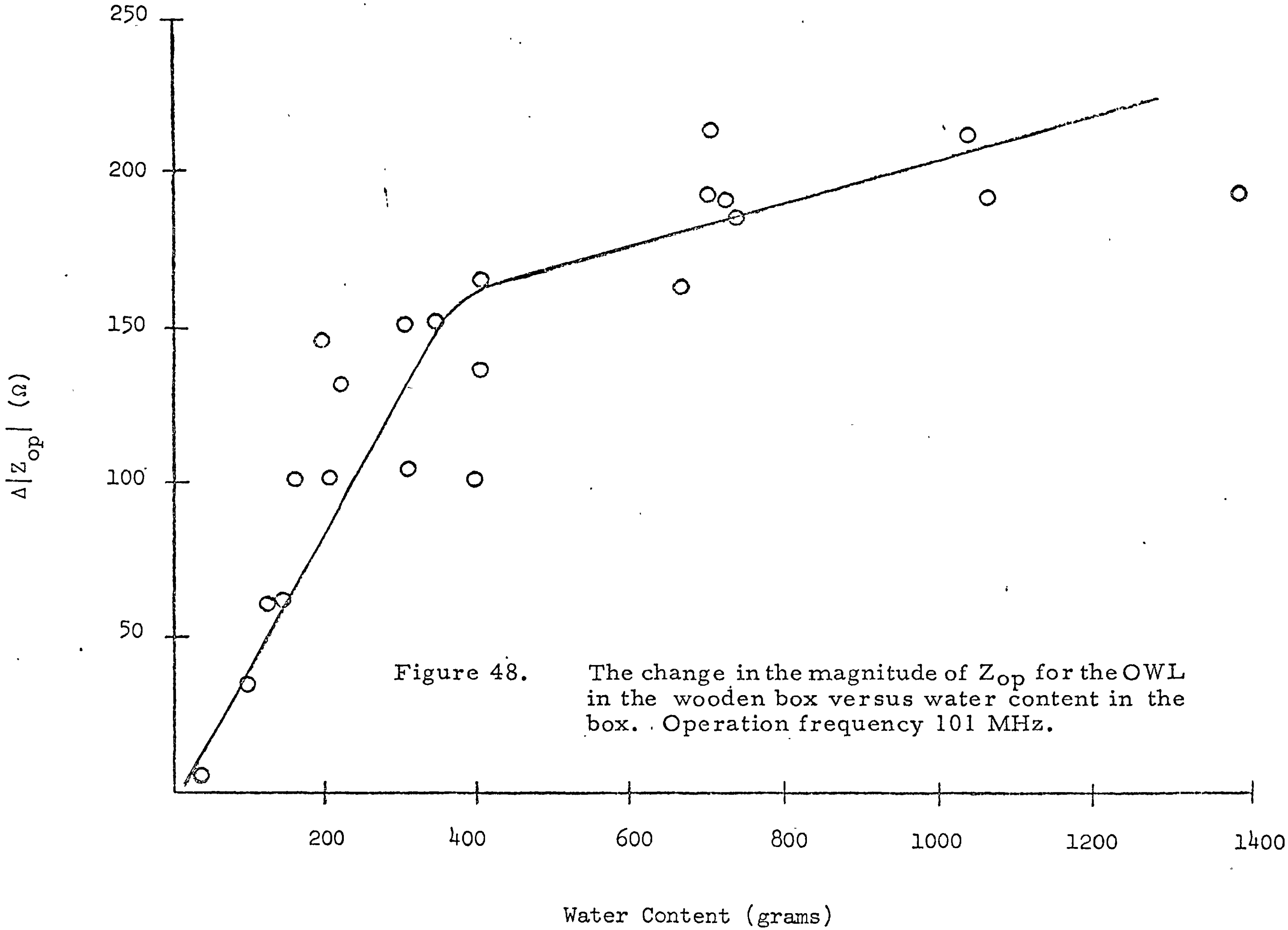


Figure 48. The change in the magnitude of Z_{op} for the OWL in the wooden box versus water content in the box. Operation frequency 101 MHz.

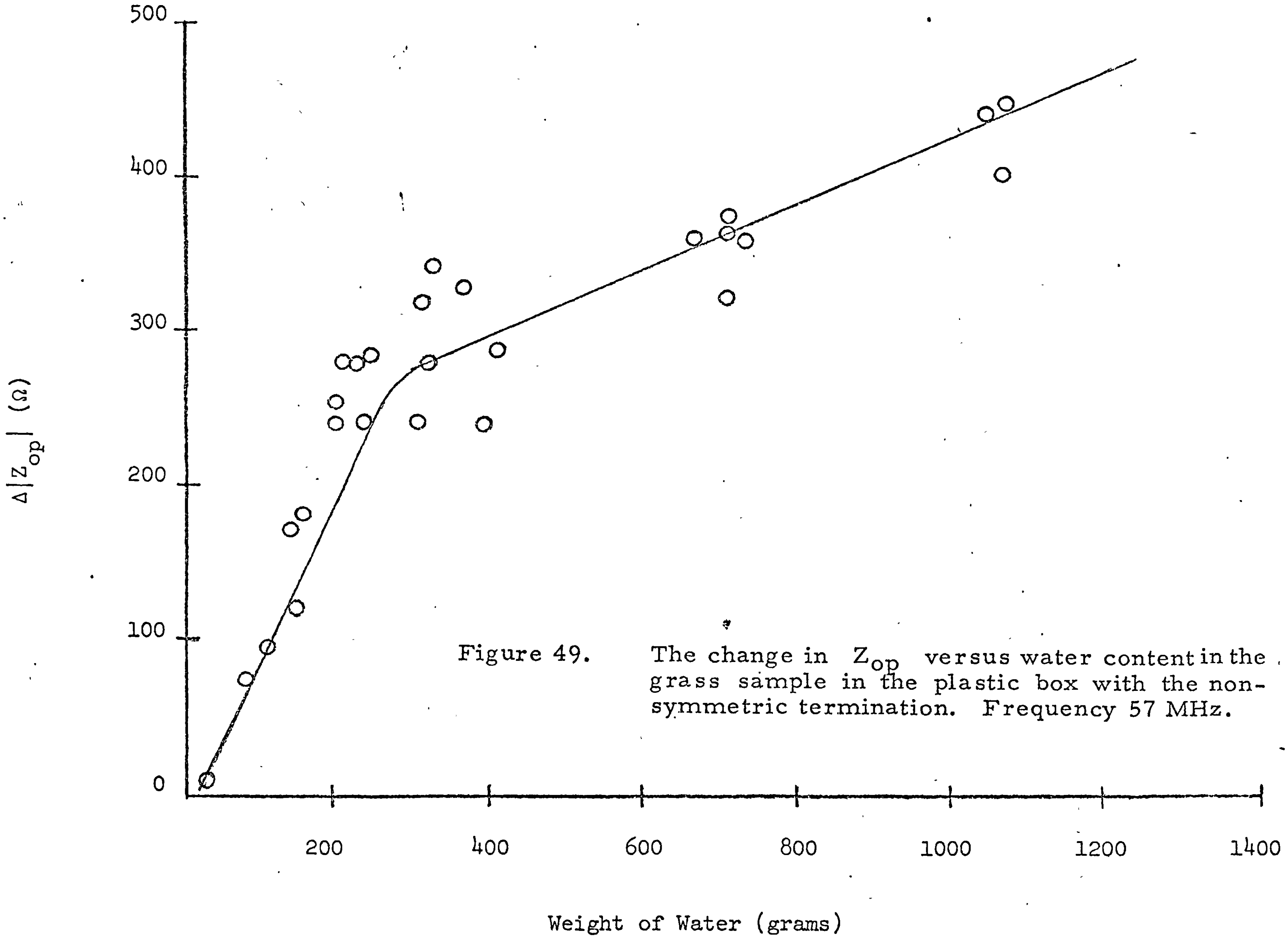


Figure 49. The change in Z_{op} versus water content in the grass sample in the plastic box with the non-symmetric termination. Frequency 57 MHz.

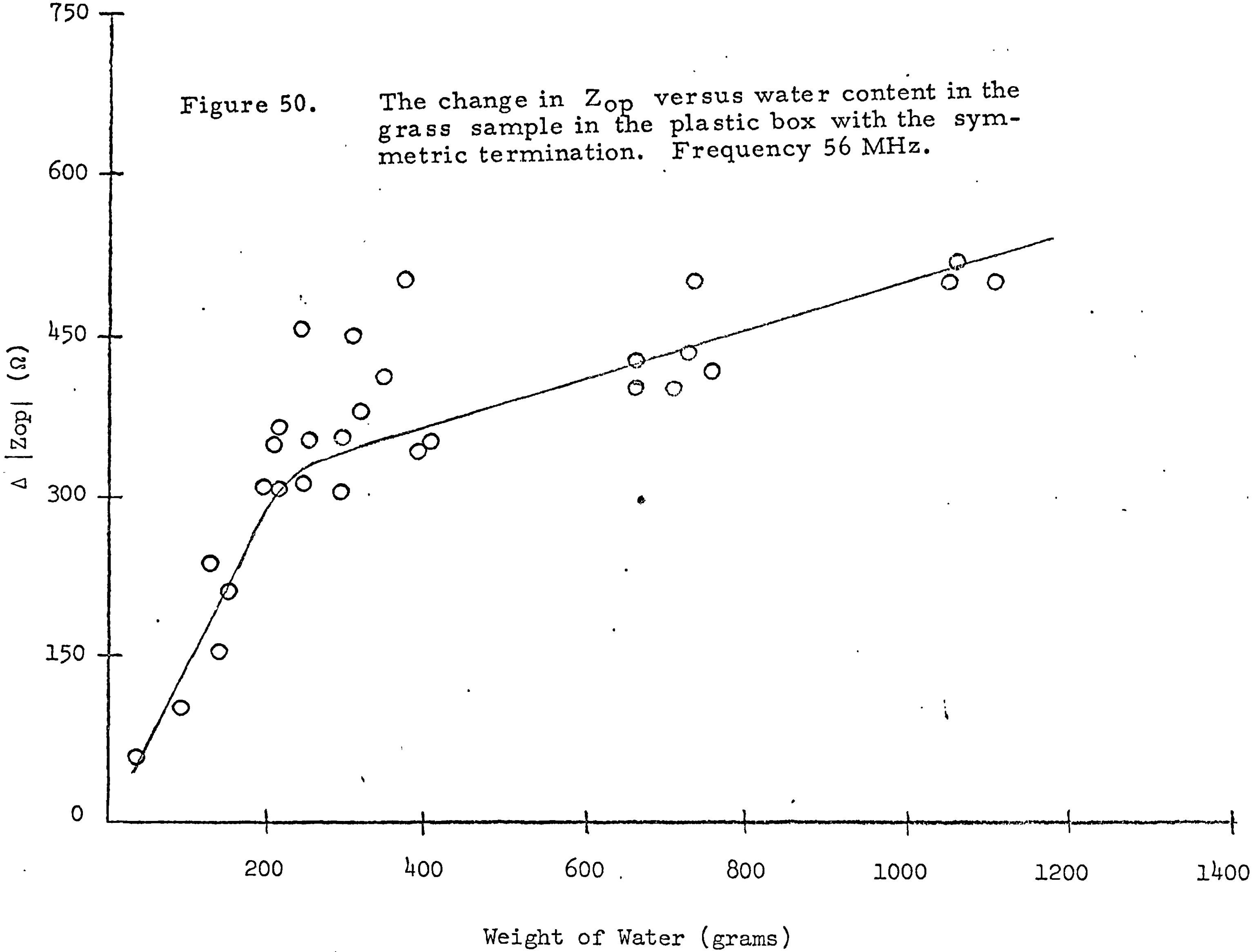


Figure 50. The change in Z_{op} versus water content in the grass sample in the plastic box with the symmetric termination. Frequency 56 MHz.

sity variation has been considerably reduced.

Figure 50 deserves special comment. This data shows the most pronounced data break at the weights of water that gave 100% moisture grass. There almost appear to be two non-related sets of data as can be seen on the figure. This "effect" if it does exist does not appear to have any significance from the standpoint of moisture measuring except that it seems to indicate a change in the sensing parameter at 100% moisture content.

It is seen in the data of Fig. 48 through 50 that considerable scatter of the data points is still present. This is still a bulk density problem. To see just how the test volumes responded to changes in sample weight the data of Figs. 51 and 52 were taken. A large sample of grass at 242% moisture was obtained. The test volume was filled in 200g. steps with the grass until it would hold no more without considerable packing. A reading of ΔZ was taken at each step. The experiment was repeated, after emptying the test volume, to measure repeatability (the curves are labeled experiment one and two). The curves of Fig. 51 and 52 indicate the OWL had reduced sensitivity for very small samples and again for very large samples. For small samples (200--300g for the data shown) the grass was in the bottom of the test volume causing reduced field coupling since the sample was some distance from the OWL. Very large samples (1000g--1200g) showed reduced coupling to the field since most of the field was contained in the grass near the OWL with little penetrating to the last grass being stacked into the top of the test volume. The repeatability data indicated an average data point spread of $\pm$ 10%.

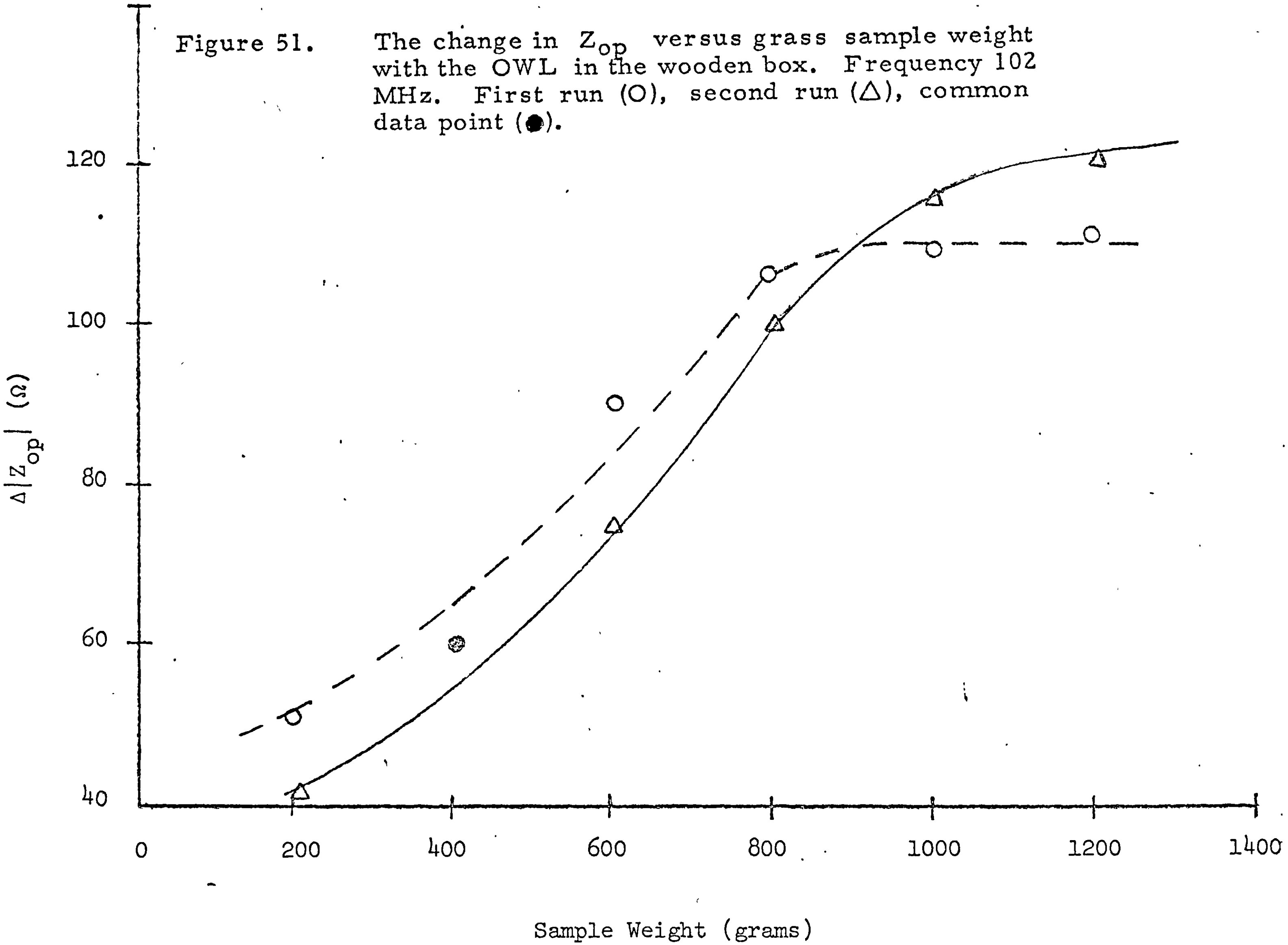


Figure 51. The change in Z_{op} versus grass sample weight with the OWL in the wooden box. Frequency 102 MHz. First run (O), second run (△), common data point (●).

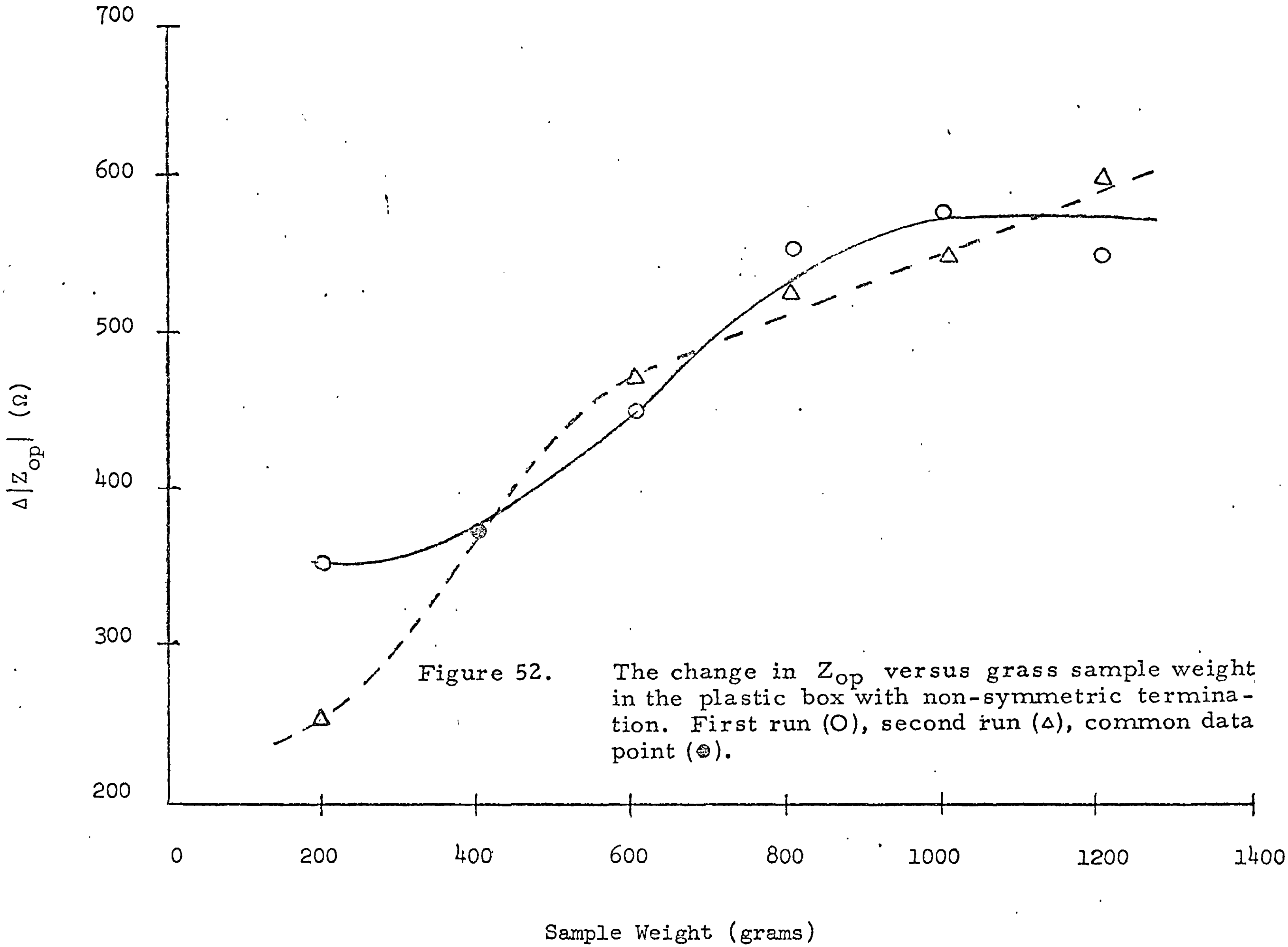


Figure 52. The change in Z_{op} versus grass sample weight in the plastic box with non-symmetric termination. First run (O), second run (Δ), common data point (⊛).

Summary of OWL box structure results.

The experiments conducted with the foliage under test being left in the test volume for the entire run showed the system to be feasible for moisture sensing. The bulk density test run with an OWL in various test boxes showed bulk density to be a major problem for samples above 100% moisture content if the sample had to be placed in the volume for each reading. The best results in terms of least data scatter were obtained when plotting sensing parameter against the weight of water in the sample box.

The 10 GHz Test Circuit

This test circuit was set up and tests started late in the program. Hence the quantity of data taken was much smaller than that taken for the open wire lines. The results were sufficiently interesting to warrant inclusion in the report, however.

The data in Figure 53 show the typical attenuation variation as the weight of the lawn grass sample in the test volume was increased. The test volume used was metal on 4 sides with two plexiglass windows and was two inches thick in the direction of propagation (box number C as listed and shown in the experimental procedures section). The two curves shown for 232% were run with the same grass on the same day. Run 1 was completed and run two was immediately started. Due to handling some drying of the grass could have occurred accounting for at least part of the downward shift of the data of the second run. Note, however, that the two curves do show quite similar shapes. Also if one picks the mean attenuation

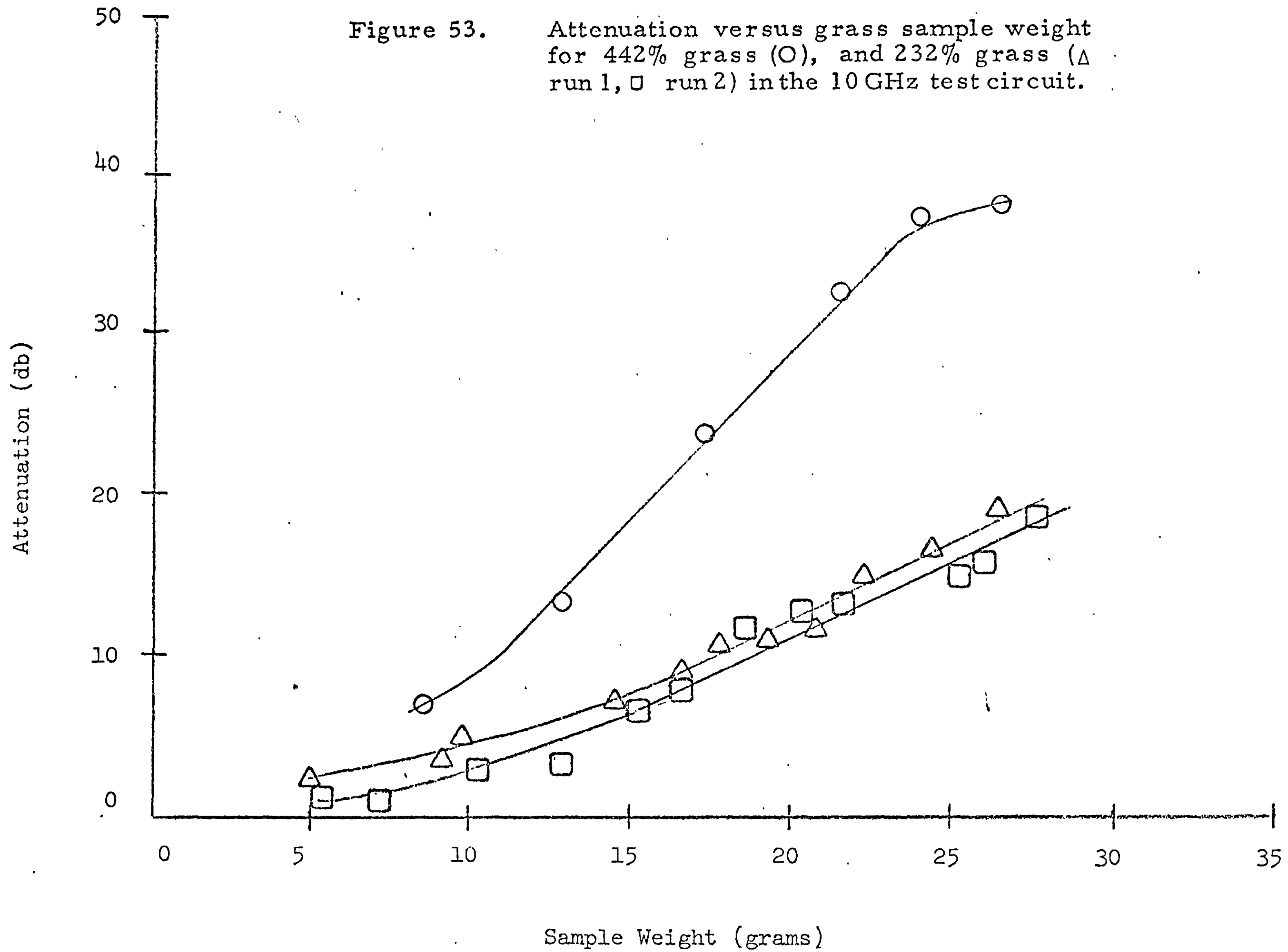


Figure 53. Attenuation versus grass sample weight for 442% grass (O), and 232% grass (Δ run 1, □ run 2) in the 10 GHz test circuit.

value at any given weight it is seen that the attenuation spread from the mean is about $\pm$ 10%. This gives a rough estimate at least of the expected repeatability of the system. The second curve of Fig. 53 is the measured attenuation versus weight for 442% moist grass. The expected upward shift of the curve is observed. Also the shapes of the curve are similar except for the "saturation" of the 442% curve at the higher weights. Note, however, that were it not for the point at 26.5g a good straight line fit could be obtained to the data points. Almost all of the data taken with the 10 GHz test circuit has shown linear attenuation versus moisture as far out in moisture as samples could be obtained or prepared. This evidence suggests that perhaps the 26.5 gram point might be in error on the 442% curve. Note the curves in Fig. 53 show non-linearity at the lower weights. This was expected since the test box was not entirely full with less than 10g. of grass. This left some large air gaps in the test box which allowed some of the signal to travel through the box unaffected by the grass sample. As the box filled up the linear curve resulted.

Figure 54 again shows two curves; this time attenuation is plotted versus percent moisture. A particular moisture content grass was placed in the box until the box was well filled but not packed. No regard was given weight until after the attenuation reading was taken. Then the amount of grass was weighed and recorded. The resulting data points are shown in Fig. 54 as solid dots (curve A). The straight line through the dots is a reasonable fit except at 350%. The curve labeled "curve B" shows the result of a linear normalization of the attenuation data to 26 grams. That is, the attenuation data at 350%, for instance, was multiplied by the ratio of

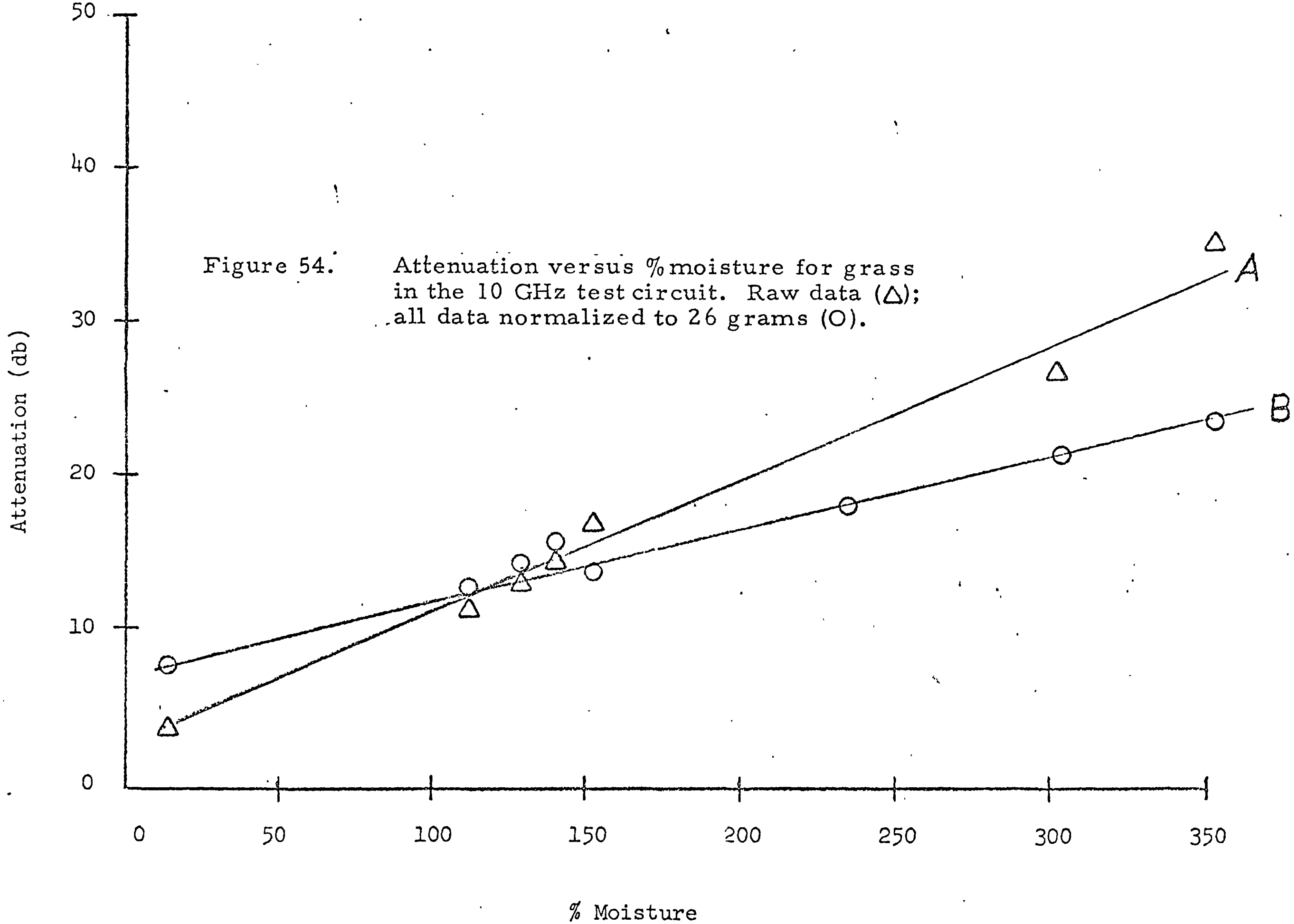


Figure 54. Attenuation versus % moisture for grass in the 10 GHz test circuit. Raw data (△); all data normalized to 26 grams (O).

26 grams to the actual sample weight to obtain an attenuation point for the normalized curve. A rather close fit of the normalized points to a straight line is obtained. Note that the extra point taken from Fig. 53 at 26g. also falls on the line. The grass samples used for obtaining Fig. 53 and 54 were different and the tests run on different days. The choice of 26g as the normalizing weight was arbitrary. However, it was noted that the test box was well filled over a wide range of grass moistures when the sample weight was around 24 to 28 grams.

The data shown in Fig. 55 was taken on the various small grains noted on the figure using test box number 2 as described in section IV. This data is included primarily to again show the linearity of attenuation versus moisture curves and to demonstrate the system can be used on other materials. Note in Fig. 55 the attenuation is higher at say 40% moisutre than at the corresponding percentage on the grass curves. This was expected for two reasons. First the small grain dimensions are on the order of a quarter of a guide wavelength at 10 GHz and hence should absorb the microwave energy more efficiently than the longer grass clippings. Also the density of the small grains is almost an order of magnitude greater than the grass. Hence even though the 10 GHz beam had to pass through only a one inch thickness of the grain (compared to 2 inches of grass) there was more water and more absorption present in the grain test box and thus the higher attenuation.

It should be pointed out that the change in the signal being measured versus moisture change is by far the greatest for the 10 GHz test circuit. Typically from the very wet to the very dry samples a 30 to 40 db change

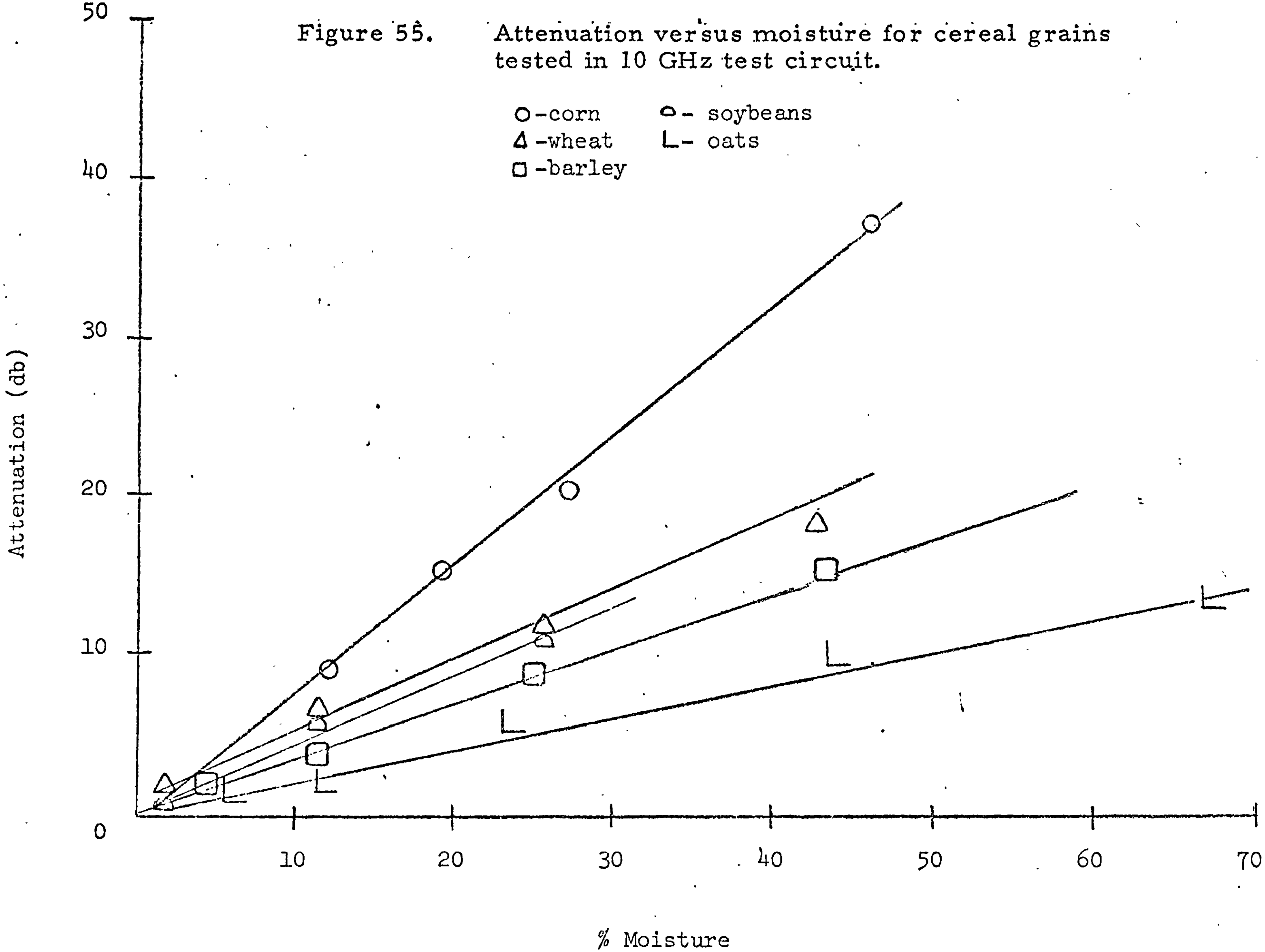


Figure 55. Attenuation versus moisture for cereal grains tested in 10 GHz test circuit.

in signal was observed. In more simple terms this is at least 1000 to 1 change in the received signal energy. The desired change can be controlled to some extent by making the test box thicker or less thick in the direction of propagation.

The 200 MHz Cavity

This test circuit was also started late in the project. It was decided that testing should be done with a cavity since it is a very widely used method of determining dielectric constants and loss tangents of common dielectric.

A typical Q curve for the cavity is shown in Fig. 56. All the data was taken with 20 gram clipped lawn grass samples and using 3 inches of the end of the cavity. The styrafoam ring mentioned previously was used to insure the test volume remained constant. Notice the curve of Q versus moisture again shows a good slope up to about 100 % moisture content and then saturates or flattens considerably. The curve could be read out to 250% (the wettest grass measured was 210%) but with considerably reduced accuracy.

The curve is obviously non-linear but is smooth and well-behaved with moisture content. It is not necessary for the moisture sensing circuit to have a linear variation of the sensing parameter with moisture so long as the curve is repeatable and predictable. A good fit to the curve in Fig. 56 is obtained with an exponential expression of the form

$$Q = ke^{-ax} \tag{30}$$

where

x = % moisture

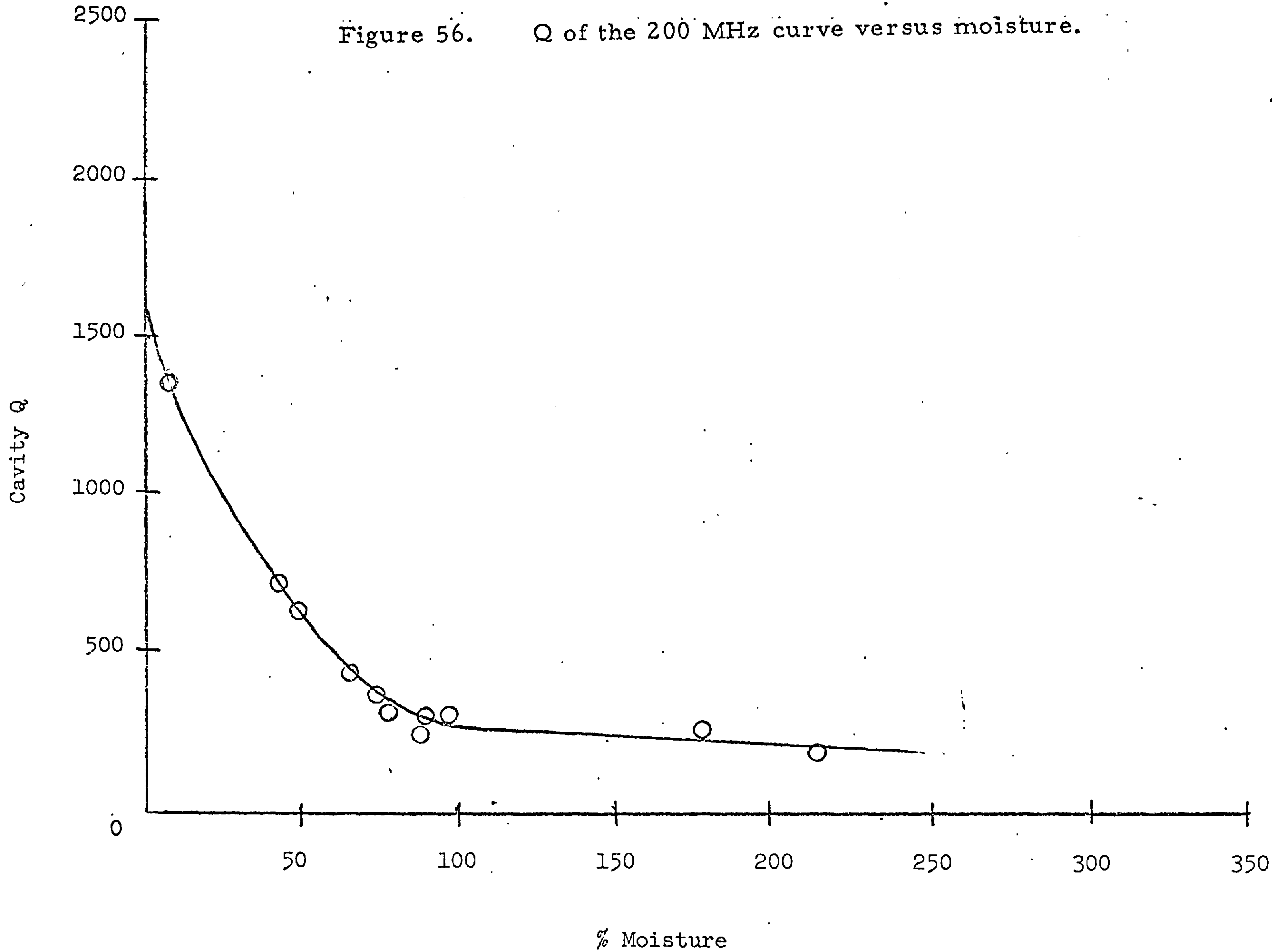
k = empty cavity Q

A = curve constant.

For the curve shown in Fig. 56 the expression is

$$Q = 158\, e^{-1.94 \times 10^{-2} x} \tag{31}$$

Figure 56. Q of the 200 MHz curve versus moisture.



This expression fits the experimental curve quite well between 0 and 100%. The data points appear to fall on nearly a straight line after the moisture exceeds 100%.

Note again that both the OWL test circuits in the boxes and the 200 MHz cavity seemed to show distinct saturation at about 100% moisture content. Further study would be necessary to determine precisely what occurs at this moisture content and what the possible cause is if such a "break point" exists.

VI. Summary and Conclusions

In this section a brief overview of the entire study is given. The systems studied as to their feasibility as moisture measuring circuits are presented in order of highest indicated feasibility to lowest feasibility (in our opinion) along with any results that appeared especially pertinant. A final set of paragraphs containing concluding remarks, a discussion of the possibility of extrapolating this study's results to other materials, and recommendations closes the report.

Summary

A total of four types of moisture sensing circuits were built and tested experimentally in this study. These four had emerged from "paper studies" as having the most chance of solving the problem of measuring the water content in foliage (both living and cut samples). The circuits were an unbalanced open wire line (OWL) operated over a ground plane, a 10 GHz attenuation circuit, a 200 MHz coaxial resonant cavity, and open wire lines surrounded by a variety of test volumes. The frequency range of the studies covered roughly 10 MHz to 10 GHz with the foliage tested including live wheat, oats, and barley plants, sagebrush, cut alfalfa hay, clipped lawn grass, and several cereal grains.

The Unbalanced OWL

The system indicated by the data to be most feasible was the unbalanced OWL operated over the wire mesh ground plane. In this section of the study open and short circuit data were taken at a number of frequencies covering 10 to 90 MHz with the line operated both resonant and non-resonant.

Three different heights of the line above the ground plane were also studied starting at 1.25 inches, then going to 3.25 inches and finally to 12 inches. A digital computer was used to operate on the primary data (Z_{op} and Z_{sc}) to arrive at the secondary parameters loss tangent (δ), relative dielectric constant (ε_r), attenuation constant (α), and conductivity (σ). The study was run from the time the plants began to grow through the wire mesh until the grain was harvested (a period of about 7 months).

The most sensitivity and greatest range over which accurate moisture content could be read for this unbalanced OWL were obtained for a short circuited, resonant line operated 1.25 inches above the ground plane. The length of line for best results was either one quarter or three quarters of a wavelength long. The sensing parameter could either be the magnitude of the short circuit impedance or the resonant frequency of the line. The short circuit impedance varied over two orders of magnitude for moistures ranging from 0 to 125% with the greatest change in the range of 0 to 75%. In the same 0 to 125% moisture range the resonant frequency of the line shifted four to five MHz with the greatest change occuring in the 0 to 40% moisture range.

This system with either sensing parameter could be adapted for remote operation. Initial installation would include finding a suitable test site, putting down the wire mesh ground plane and setting up the line and sensing circuits. A calibration curve for the particular foliage being tested would also have to be established. After the calibration curve was established no operator would be required for the OWL except at a central data terminal to receive and analyze the data being sent from the OWL field site.

The non-resonant data indicated either Z_{op} or Z_{sc} could be used to sense the moisture but that the slope of the curves was small beyond about 75% moisture content. Thus accurate calibration of the system for moistures greater than 75% would be difficult. Of the non-resonant secondary parameters, the loss tangent (δ) appeared to be the most sensitive to moisture content. From the data the best frequency and line height were respectively 50 MHz and 1.25 inches. The best non-resonant system would then be, from the data, set up to measure loss tangent (δ) at 50 MHz with a line height of 1.25 inches. To conveniently measure (δ) requires an operator to change the line termination plus a digital computer to analyze the data.

It should be pointed out that while the data taken for the unbalanced OWL over the ground plane do indicate feasibility of this system, the expected system accuracy and the effects of bulk density on the procedure are not established by the data. Perhaps field testing of this system would be the fastest way of examining the above two questions. Experience gained from this study suggests that bulk density effects could be calibrated out of this system since the foliage grows little after the testing season starts (when the foliage begins to dry). Also, the sensing parameter can be measured quite accurately. The accuracy of the system would depend more on how external influences scatter the data points.

The Balanced OWL

The next system showing possible feasibility was the OWL in the box used to test the sagebrush. Once again, the brush was not moved during the test and hence little data scatter occured because of positioning. the

sample. Note, however, that it would be difficult to calibrate this system for use as a remote terminal since a sample must be cut and placed in the box. The drying rate of the cut sample would not correspond to that of living foliage and hence the drying curve as monitored by the box would not be too useful.

The 10 GHz Attenuation Circuit

This system demonstrated as much feasibility as the above discussed balanced OWL. The data taken did show some scatter since cut samples were placed in a test volume in this study. Thus the bulk density problem was present. However, the data did indicate a linear change in attenuation with moisture content for the clipped lawn grass and the small cereal grains. Also it was demonstrated that a sample weight of 26g. might be used to reduce the data scatter. This circuit was the only system tested that did not show saturation at high moisture content of the material under test. The change in sensing parameter (attenuation) for this circuit was about 40:1 over a 0 to 400% moisture range.

The 10 GHz attenuation circuit might also be adapted for remote operation. The sensing parameter was attenuation as measured on a calibrated attenuator in the laboratory setup. However, the principal involved was basically the measurement of path loss between two horn antennas. Thus it would not be necessary that a sample be placed between the horns; it could be allowed to grow up between them. As with the unbalanced OWL over a ground plane the system would have to be calibrated in the field to establish a calibration curve and establish the system accuracy. An additional problem exists with the 10 GHz system

in that energy would be purposely radiated to measure path loss caused by the growing foliage. Care would be needed to insure that Federal regulations regarding the radiation of electromagnetic energy were not violated.

The 200 MHz Cavity

The cavity resonator showed a rather high sensitivity to moisture changes in the clipped lawn grass used in the study. Changes in the sensing parameter (Q) of almost an order of magnitude were observed over the moisture range of 0 to 250% with most of the change coming between 0 and 100%. The curve, while not linear, did fit rather well to an exponential variation. The circuit has several drawbacks, however. It uses a fairly small sample which must be placed in the end of the coaxial cavity. The filling procedure was found to be somewhat tedious. Bulk density variation in the samples was a problem with this circuit as the sample had to be placed in and removed from the test volume for each data point. A final drawback was that the measurement of the cavity Q was not as straightforward as was the measurement of the other sensing parameters used in the study. Using equipment that would be commonly available, an operator would have to make three readings for each data point to obtain the Q. Obviously a single reading for each data point would be much more desirable.

The Balanced OWL with Test Boxes

The data taken for the three different test boxes were not encouraging. Bad data scatter occurred for measurements made with constant sample weight, using a "full volume," and in tests using enough grass to

see no more change in the sensing parameter. The data was also unsuccessfully analyzed to ascertain if a normalizing weight similar to the 26g of the 10 GHz test circuit would be found. The data indicates that the bulk density problem is present to such an extent with these circuits as to make them unreliable as moisture sensing circuits. The latter statement could be modified somewhat if moisture contents of less than 100% were to be considered. From 0 to 100% moistures less data scatter was observed. In this range a fixed sample weight could be used such that all samples would be fit into or nearly fill the test volume.

The sensitivity of the open circuited balanced OWL in a test box was good but not as high as several of the other circuits examined. The use of the wooden box and the terminated box did show that perhaps a termination could be designed to give better sensitivity. A final point on these structures is that they could not be used for remote sensing without an operator. The sample must be placed in and removed from the test volume for each data point.

CONCLUSIONS

The data presented in this report indicate there are several ways of sensing moisture in foliage using radio frequency energy and techniques. It is possible to monitor moisture changes in living foliage and, if desired, to do the monitoring at a remote field site without the necessity of an operator at the site. An open wire line above a ground screen can detect both the drying (curing) of a foliage and transient periods of additional moisture in the foliage caused by rains. With the line only a few inches ($1\frac{1}{2}$" to 3") above the ground plane, changes in the humidity of the air will have little effect

because the electromagnetic fields will not appreciably escape the foliage and the humidity of the air between the stems and leaves changes little with the overall humidity. The system should be calibrated with a reading when the foliage is mature and starting to cure. The calibration involves taking a reading, probably the impedance, and a xylene sample. Perhaps a second xylene sample would be needed after some drying had taken place to locate the sample on a known curve of percent moisture versus impedance. The equipment needed to generate the test signal and measure the desired parameter should not be too complex or costly. For example, a crystal oscillator, amplifier, and current monitoring device would indicate the impedance.

Except for the OWL mounted above the screen, the largest problem encountered was how to sense only moisture in the foliage and to keep the sensing system from responding to bulk density changes or changes in how the sample occupied the test volume. These two variables are not considered to be two separate problems because they were so closely related. The study showed that dry grass had a small bulk density and hence a large volume per unit weight. The reverse was true for very wet grass. The dry sample might occupy the RF test volume in a uniform fashion, but the wet sample of equal weight would occupy only a small portion of the test volume. On the other hand a "full" test volume was difficult to define, particularly for wet samples (high bulk density), since the amount of packing and the way of packing the test volume yielded a wide variation in sample weights and bulk density variations in the test volume. The problem can be avoided by using sensing systems that do not require the sample to be moved during the testing season. With a system such as the unbalanced

OWL over the wire mesh ground plane or the 10 GHz path loss system it is possible to "calibrate out" bulk density in living foliage by normalizing the data to the initial reading taken on the growing (or curing) sample.

The data taken in this study used only a small range of foliage types. As indicated by the 10 GHz data on the clipped lawn grass and the cereal grains there should be no reason to expect that the results could not be extrapolated to other types of foliage such as cheat grass or other common grasses and brush found in areas where the fire danger rating system is used. It is possible that a different calibration curve will exist for each type of grass although the data taken with the unbalanced OWL over the ground plane did show the OWL was not sensitive to the different grasses used in the test box (wheat, oats, and barley).

The final point to be discussed is what the data indicate should be done next. First, most further work with the feasible sensing systems should be done at field sites.

Before a field operation is begun, the instrumentation should be developed which would provide the necessary data, be able to operate in the field, and be reasonably priced. A complete test procedure would be planned before the apparatus is installed. Then extensive tests should be conducted. However, due to the single growing season per year and the immovable nature of the device, "extensive tests" means a large number of test sites. Calibration curves should be made for the foliages which are of interest. System accuracies, reliability, and economics would be determined. Then an evaluation can be made by the Forest Service as to the applicability of the moisture measuring system to their needs.

An annoyance found throughout the study was the lack of a theoretical model to which the data could be compared. The primary reasons for the lack of a model were insufficient information on what the dielectric properties of the foliage were and lack of a concerted effort to obtain such a model. It would be worth while, if this area is to be pursued further, to use the data and experience gained from this study to formulate a theoretical model. If a practical model could be obtained much time could be saved in experimental work to ascertain system accuracy and system response to various influences.

APPENDIX A

More of the details of the analysis for the OWL are given in this appendix. The expressions developed are those used in the computer reduction of data taken in the course of the study.

Using equations (7), (11), (12), and (13) from the text one has

$$\Gamma_o = \frac{1}{\ell} \text{ Tanh}^{-1} \left(\frac{Z_{sc}}{Z_o}\right) \tag{A-1}$$

$$= \alpha_c + j\beta_c = \text{propagation constant of the conductor} \tag{A-2}$$

where

ℓ = the physical length of the OWL. Equations (A-1) and (A-2) may be solved for α and β to yield

$$\alpha_c = \frac{1}{4\ell} \ln \left\{ \frac{\left[1 + r\ell\left(\frac{Z_{sc}}{Z_o}\right)\right]^2 + \text{Im}^2\left(\frac{Z_{sc}}{Z_o}\right)}{\left[1 - r\ell\left(\frac{Z_{sc}}{Z_o}\right)\right]^2 + \text{Im}^2\left(\frac{Z_{sc}}{Z_o}\right)} \right\} \tag{A-3}$$

$$\beta_c = \frac{1}{2\ell} \left\{ n\pi + \text{Tan}^{-1} \left[\frac{2 \text{ Im}\left(\frac{Z_{sc}}{Z_o}\right)}{1 - \text{Re}^2\left(\frac{Z_{sc}}{Z_o}\right) - \text{Im}^2\left(\frac{Z_{sc}}{Z_o}\right)} \right] \right\} \tag{A-4}$$

where n = nearest number of quarter wave-lengths in the line

r = resistance per unit length of line (see eq. (2) section III)

Im, Re = Imaginary part of, Real part of.

Using the analysis of section II, one has

$$Z_o = \left(\frac{r + j\omega L}{g + j\omega C}\right)^{\frac{1}{2}} \tag{A-5}$$

$$\Gamma_c = (r + j\omega L)(g + j\omega C)^{\frac{1}{2}} \tag{A-6}$$

and hence

$$\omega C = \mathrm{Im}\left(\frac{\Gamma_c}{Z_o}\right) \tag{A-7}$$

To normalize to air dielectric one may write

$$\frac{\omega C}{\omega' C'} = \frac{\mathrm{Im}(\Gamma_c/Z_o)}{\mathrm{Im}(\Gamma_c'/Z_o')} \tag{A-8}$$

where the primed quantities refer to air dielectric. From (A-8) one may then write (assuming the relative permeability $\mu_r = 1$)

$$\epsilon_r = \frac{f'}{f}\,\frac{\mathrm{Im}(\Gamma_c/Z_o)}{\mathrm{Im}(\Gamma_c'/Z_o')} \tag{A-9}$$

The loss tangent is defined as

$$\delta = \frac{\sigma}{\omega\varepsilon} = \frac{g}{\omega C} \tag{A-10}$$

or from (A-5) and (A-6)

$$\delta = \frac{\mathrm{Re}(\Gamma_c/Z_o)}{\mathrm{Im}(\Gamma_c/Z_o)} \tag{A-11}$$

Note also that

$$\sigma = \omega\varepsilon\delta \tag{A-12}$$

The secondary parameters of the OWL can be calculated then using (A-9), (A-11), and (A-12) along with (14) and (15) in section III of the report.

APPENDIX B

Several of the electrical aspects of the OWL are given further consideration in this Appendix. Specifically, the radiation characteristics of the short circuit used are examined to help identify the frequency range (or line length) over which the short does not act as an antenna. Also briefly discussed is the question of where the stored energy is on the OWL. This discussion gives some feel for what the sensing volume around the line should be.

Radiation Resistance

The theory used to arrive at the radiation resistance is rather tedious to work with and even more tedious to read. Suffice it to say then that the radiation resistance expression for the short on the OWL was derived using Maxwell's equations, the appropriate boundry conditions and the complex Poynting's vector to calculate the radiated power. The radiated power expression can be written in the form

$$P_{rad} = I^2 R \qquad \text{(B-1)}$$

for the shorted transmission line. It is then found that the radiation resistance is

$$R_{rad} = 789 \left(\frac{d\ell}{\lambda}\right)^2 \qquad \text{(B-2)}$$

where $\lambda = \dfrac{3x10^8}{f}$ meters

$d\ell$ = line spacing = 2 times the height of the unbalanced OWL above the ground plane.

Physically the radiation resistance can be looked at as a measure of

how effective an antenna is as a radiator. Just as a high resistance in a wire carrying current causes high heat loss in that line, a high radiation resistance for the shorted transmission line implies a large loss of power due to radiation.

It must be pointed out that several simplifying assumption were used in the theory to allow a solution to be obtained. Hence equation (B-2) is an approximation to the actual shorted OWL but it is valid to look at the expression to obtain a feel for how the OWL will perform (or hopefully not perform) as an antenna.

The expression (B-2) is plotted Fig. B-1 for line spacings that correspond to the line heights used with the unbalanced OWL over the ground plane. Also shown on the figure are measured values of line resistance that include both radiation resistance and conductor loss. The major feature to notice is that the calculated and measured radiation resistance increases rapidly with height (line spacing) and frequency. For moisture sensing with a shorted OWL one desires the energy be in the stored fields, not radiated into space. The figure then implies that the line should be kept as low as practical and the frequency as low as possible to decrease radiation loss.

Location of the Power on the OWL

It is desireable to have some idea where the stored energy is along the OWL and how far it extends away from the line. Actually the stored fields extend to infinity on either side of the line but for practical purposes the sensing fields are within a meter or a few meters from the line.

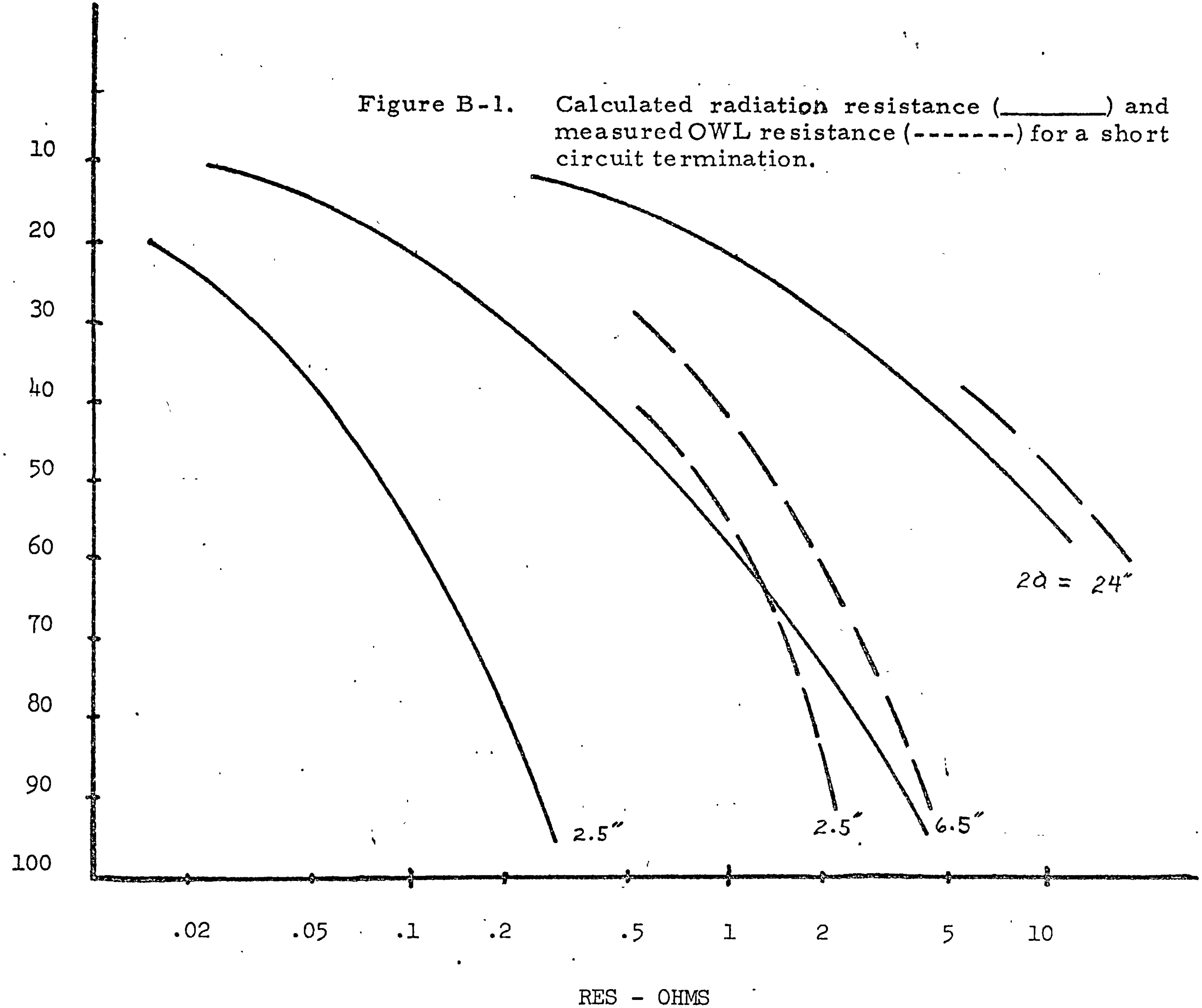


Figure B-1. Calculated radiation resistance (________) and measured OWL resistance (-------) for a short circuit termination.

Once again Maxwell's equations are used on a balanced two wire line spaced a distance (2a) apart. The results can be applied to a single wire line spaced a distance (a) above a ground plane. At first a line was considered that had no reflections from the termination (line terminated in its characteristic impedance Z_o). It was desired to find the percentage of the total power into the OWL that traveled down the line within a circle of radius ρ around the line. The results are shown graphically in Fig. B-2 The plot shows the percent power versus the ratio of the circle radius ρ to half the line spacing. Thus from the graph one has for a circle of radius $\rho = a$ that 40% of the power is contained in this circle for the line terminated in Z_o. Note that this circle is the area inside the two transmission lines.

Now suppose the line is terminated in a short circuit. The results would be similar for an open circuit termination. When the line is shorted there will be a standing wave on the line and hence it is expected that the power would extend further from the line in some places than it does in others. A plot of the solutions to Maxwell's equations for the power along the line for the shorted OWL is shown in Fig. B-3. The ordinate shows the normalized power into the line while the abscissa is the length of line away from the short circuit. For convenience the normalized power into the line for the matched case is also shown. Note that if the line extends a quarter wavelength from the short the power for the shorted line extends four times further from the line that when Z_o terminates the line. Suppose one defines the point where useful moisture sampling stops as the circle containing 82% of the power. From Fig. B-2 the radius of this circle is

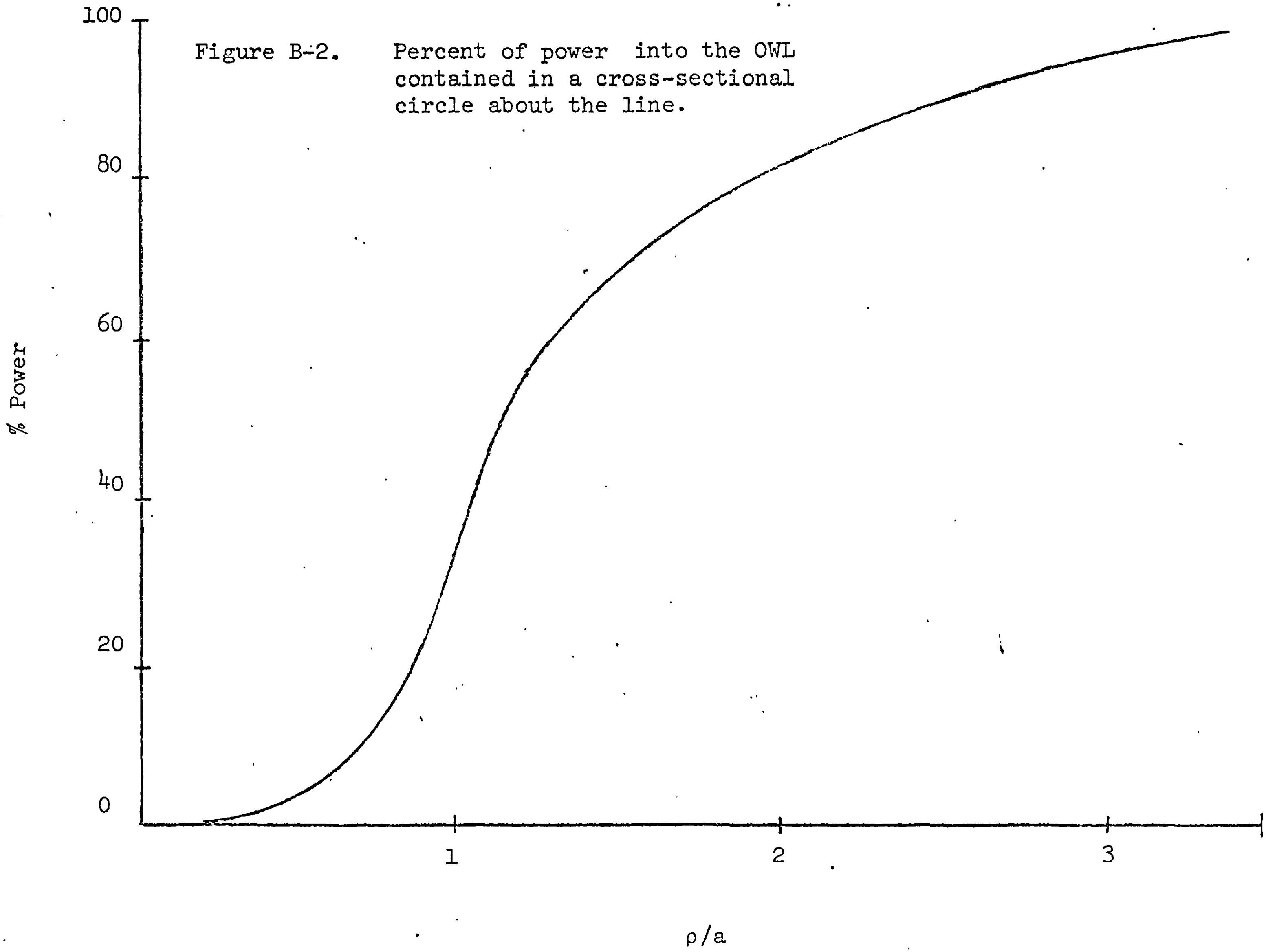


Figure B-2. Percent of power into the OWL contained in a cross-sectional circle about the line.

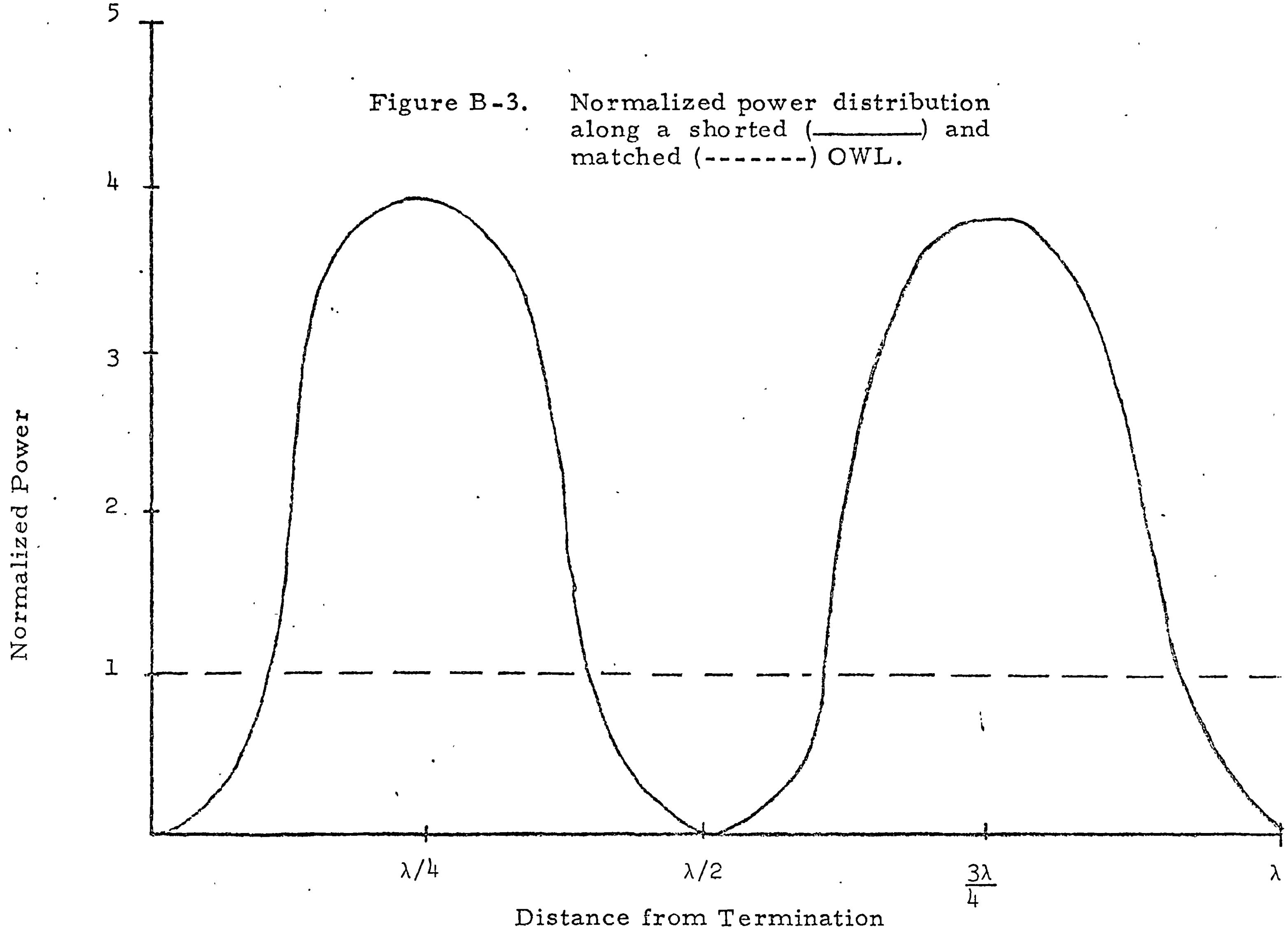


Figure B-3. Normalized power distribution along a shorted (————) and matched (-------) OWL.

constant at $\rho = 2a$ for a matched line. For the shorted line, a quarter wavelength away from the short the circle is 4 times bigger or $\rho = 8a$. Moving a half wave from the short, the line has a sensitivity of zero and so on. The 82% surface for the shorted line looks like a series of onions laid end to end.

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